Hillslope and watershed scale hydrological processes and grazing management in a Dartmoor catchment, Southwest England

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by

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Abstract

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Erik W. Meyles

Concerns have been raised on the deterioration of heather moorland due to management in the UK. A study was therefore conducted on the impacts of moorland management on the soils and hydrology of a catchment on Dartmoor. Soil moisture was measured grid-wise using TDR on 19 occasions. At 23 sites within this grid, physical properties of the topsoil were obtained. At three locations, tensiometer nests were installed, recording soil suction at 10 cm depth intervals. At the catchment scale, stream discharge and rainfall were recorded. Grazing densities within the watershed were estimated and the observed patterns were related to vegetation types.

Results from the TDR grid showed that in dry conditions, soil moisture patterns are heterogeneous in contrast to a more uniform pattern in wet periods. A threshold soil moisture content of about 0.60 $cm^3\ cm^{-3}$ divides the two conditions. The exponential relationship between average hillslope soil moisture content and stream discharge also revealed the division between wet and dry states. A regression analysis showed that during dry conditions, the vegetation plays a significant role in determining the soil water status. During wet conditions, topography becomes more important. In these conditions, the soil water movement is mainly lateral, whereas in the dry state, this is vertical in the soil profile. Tensiometer data showed that most soil water movement is in the topsoil.

Analyses suggested that soil moisture under vegetation classes associated with higher grazing pressures is higher in similar topographic conditions. Soil bulk density is higher and the total porosity is lower near the soil surface. This suggests that less rainfall is required to reach the soil moisture threshold and water will be transported laterally down the slope.

A heather burning experiment revealed that the direct effect of temperature is shallow. Soil moisture levels do not change over the course of the burn. However, in dry situations during summer, soil moisture contents under burned plots are higher than under unburned vegetation probably due to reduced transpiration. If this effect is similar at the hillslope scale, when the soil is wetting up, the soil moisture threshold value could be reached at an earlier stage and accelerated lateral water movement could be the result.

It can be concluded therefore, that moorland management could accelerate water movement on the hillslopes causing higher discharge peaks in wet periods and consequently low flows in summer. However, the effects are subtle and encouraging vegetation heterogeneity could play a role in buffering water to prevent loss to the stream.

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Author's declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Publications:

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Meyles EW, Williams AG, Ternan JL. 2001. Effects of grazing on soil properties and hydrology of a small Dartmoor catchment, Southwest England. IAHS publication 268: 279-286.

Meyles EW, Williams AG, Dowd JF, Ternan, JL. 2001. Soil moisture patterns and runoff generation in a small Dartmoor catchment, South-West England. Freiburger Schriften zur Hydrologie. Proceedings of the International Workshop on Runoff Generation and Implications for River Basin Modelling. Band 13: 28-36.

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Effects of grazing on soil properties and hydrology of a small Dartmoor catchment, Southwest England. 6th Scientific Assembly of the IAHS - 'A new hydrology for a thirsty planet'. 18-27 July 2001, Maastricht, The Netherlands.

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Chapter 1: General introduction

1.1 Background and problem definition

The research detailed in this thesis considers the water movement in a small catchment on Dartmoor and the impact of moorland management on the hillslope hydrology. This subject is of critical importance both in terms of nature conservation and the management of water resources in the largest moorland area of South West Britain.

There has been a gradual decline of heather moorland in the UK due to overgrazing and consequently the need for frequent extensive burning is increasing (Bunce and Fowler, 1989; Bardgett *et al.,* 1995; Thompson *et al.* 1995a; English Nature, 1998). These land management pressures increased until recently with detrimental consequences for vegetation, soils and hydrology (Mowforth and Sydes, 1989; Weaver *et al.*, 1998; Johns, 1999) and they could also affect upland reservoirs used for drinking water supply (Johns, 1999). In the future, the less intensive nature of hill farming may also have important repercussions for the environment.

Moorlands are a great natural asset in Great Britain and can be regarded as a habitat with a unique flora and fauna (McTernan, 1993). The occurrence of natural moorlands in Britain is limited and the majority of the moorlands are man-made which reflect a long history of land use (Gimingham, 1975; McTernan, 1993; Thompson *et al.,* 1995b). Within Europe, similar moorlands are rare, but in Britain they are widespread. Most British moorlands are situated in Scotland, Northern England and Wales, each with their own special character due to the regional interaction of geology, climate and management (Gimingham, 1975; Fielding and Haworth, 1999).

The most southerly moorlands occur in Southwest England. Three major areas can be distinguished, namely: Dartmoor, Exmoor and Bodmin Moor, but even in this small region, differences between these moors are distinct. Dartmoor and Bodmin Moor are situated on a granite outcrop, whereas Exmoor consists of sandstones and slate (Findlay *et al.,* 1984). Exmoor is lower than Dartmoor, and arable land occupies a relatively large area. Dartmoor is by far the largest of the three, and is characterised by two large blanket bog areas (Findlay *et al.,* 1984).

The Dartmoor environment is a very dynamic system and the landscape has been changing continuously throughout history. Vegetation, soil and hydrology have been altered, often subtly, due to extensive and intensive management practices. Tin streaming and granite quarrying have had important, largely irreversible impacts on the geology, topography and soils. Likewise, agricultural activities have had a much more gradual but serious influence on the soils of Dartmoor in general. Since Neolithic times, grazing and burning management have probably been irregular, but at least for the last 150 to 200 years, most of the moorlands have been managed by a cycle of periodic burning and grazing (Thompson *et al.*, 1995b). In the 19th century, farmers around Princetown started improving their lands, altering the soil. Winter hardy breeds of sheep were introduced, changing the grazing regime from seasonal to the entire year, increasing the grazing pressure (Sansom, 1999). Since the 1940s, farmers have been supported by governmental policies in order to ensure upland communities remained viable. Agricultural subsidies encouraged farmers to increase sheep numbers. Although Dartmoor received a National Park status in 1951, one of the main objectives was to pay close attention to the local economy, giving the local farmers much freedom to intensify. During the 1970s, much of the fringe moorland was lost due to land improvement for agricultural purposes. Ploughing, fertilising and reseeding altered large areas of the so-called 'newtakes', causing a sudden irreversible change in the landscape of Dartmoor. During the 1970s and 1980s, the number of sheep on the unenclosed hill areas increased (Sansom, 1999) in response to the headage payments for ewes and cattle known as Hill Livestock Allowances (Evans and Felton, 1987; MAFF, 1993; Thompson *et al.,* 1995b; MAFF, 1997). Problems of poor vegetation management, overgrazing and erosion were recognised in the early 1980's, leading to the Dartmoor Commons Act in 1985 (Act of Parliament, 1985), in which improving of unenclosed land was discouraged, but little was done to prevent the increasing sheep numbers on the unenclosed moors (Evans, 1996).

Since the early 1990's, there has been increasing awareness that areas of heathland on Dartmoor are gradually declining and are being lost to grass moor. Overgrazing is thought to be mainly responsible for this decline, but there are also indications that burning has been on the increase and is also contributing to the deterioration of heather (Bates, 1998, pers. comm.).

Additionally, concerns have been raised about the loss of biodiversity on Dartmoor. Therefore, in 2001, the Dartmoor Biodiversity Action Plan was published (Dartmoor National Park Authority, 2001). This publication was a response to concerns about biodiversity loss at the global scale, expressed at the Rio Earth Summit in 1992. The Action Plan followed similar plans at European, national and regional scale. In collaboration with many stakeholders on Dartmoor, the plan (Dartmoor National Park Authority, 2001) outlines

> "the objectives, targets and action considered necessary to protect and enhance the wildlife heritage of Dartmoor over the next ten years".

In this context, agri-environment schemes, such as the Dartmoor Environmentally Sensitive Area Scheme (ESA) and to a lesser extent the Countryside Stewardship and Hill

Farm Allowances (all part of the England Rural Development Programme (EDRP; DEFRA, 2002) are regarded as potentially the major deliverer of biodiversity targets on agricultural land in the National Park (Dartmoor National Park Authority, 2001).

Since 1994, hill farmers have had to adapt to the Environmentally Sensitive Area status on large areas of Dartmoor in which nature conservation payments are made to maintain and enhance the landscape (MAFF, 1998). One of the main environmental objectives of the moorland ESA is to reduce grazing levels to a level that does not suppress the cover of heather. Farmers are encouraged by grant payments to reduce stocking levels, especially during winter, when heather is most vulnerable to grazing. The introduction of the Dartmoor ESA is anticipated to increase the extent of heather, but the lasting effect of high stocking densities on Dartmoor over the last decades is as yet unknown.

In other moorland areas throughout Britain, locations with increasing grazing intensities have been associated with increasing erosion (Evans, 1998; Sansom, 1999) and quick runoff responses (Evans, 1996) leading to flooding in winter, and low flows in summer (Sansom, 1997). It has been suggested that reduced vegetation cover and decreased infiltration due to compaction may account for the observed runoff increase (Evans, 1996; Sansom, 1996). In addition, burning of peaty soil surfaces may reduce the water storage capacity of the soil, increasing the storm runoff and decreasing the natural storage in the deeper layers (Johns, 1998). These effects can have major impacts on reservoirs situated in moorland areas (Johns, 1998), such as found on Dartmoor, due to increased sediment production and flashy regimes.

Substantial research on the gradual vegetation change has previously been carried out both on Dartmoor (Kent and Wathern, 1980; Weaver *et al.*, 1998) as well as in other moorland areas (*e.g.* Welch, 1984; Armstrong and Milne, 1995; Clarke *et al.*, 1995; Hester and Baillie, 1998), but the effects of management on the soils and hydrology are still largely unknown. A possible cause of this lack of interest is the relatively subtle change in management pressures through the last six decades, so that the extent of the changes and their wider implications have largely passed unrecognised (Sansom, 1999). Research that has been carried out mostly focuses on plot-size changes, both in burning and grazing experiments, but the wider perspective is mostly unexplored.

This study focuses on the hydrology of a Dartmoor hillslope and its catchment but briefly considers the effects that moorland management can have on soil and hydrological properties at a wider scale as well. Figure 1.1 is a generalised view of the Dartmoor hydrological system and shows the most important factors directly or indirectly influencing the hydrology of the Dartmoor moorland environment.

The two main variables influencing the hydrology at the local scale are the topography and the macro-climate. The complex interaction between other variables such as geology, soils and vegetation also has an important influence on soil water pathways at the plot, hillslope and catchment scale. The combinations of these components determine the hydrological processes.

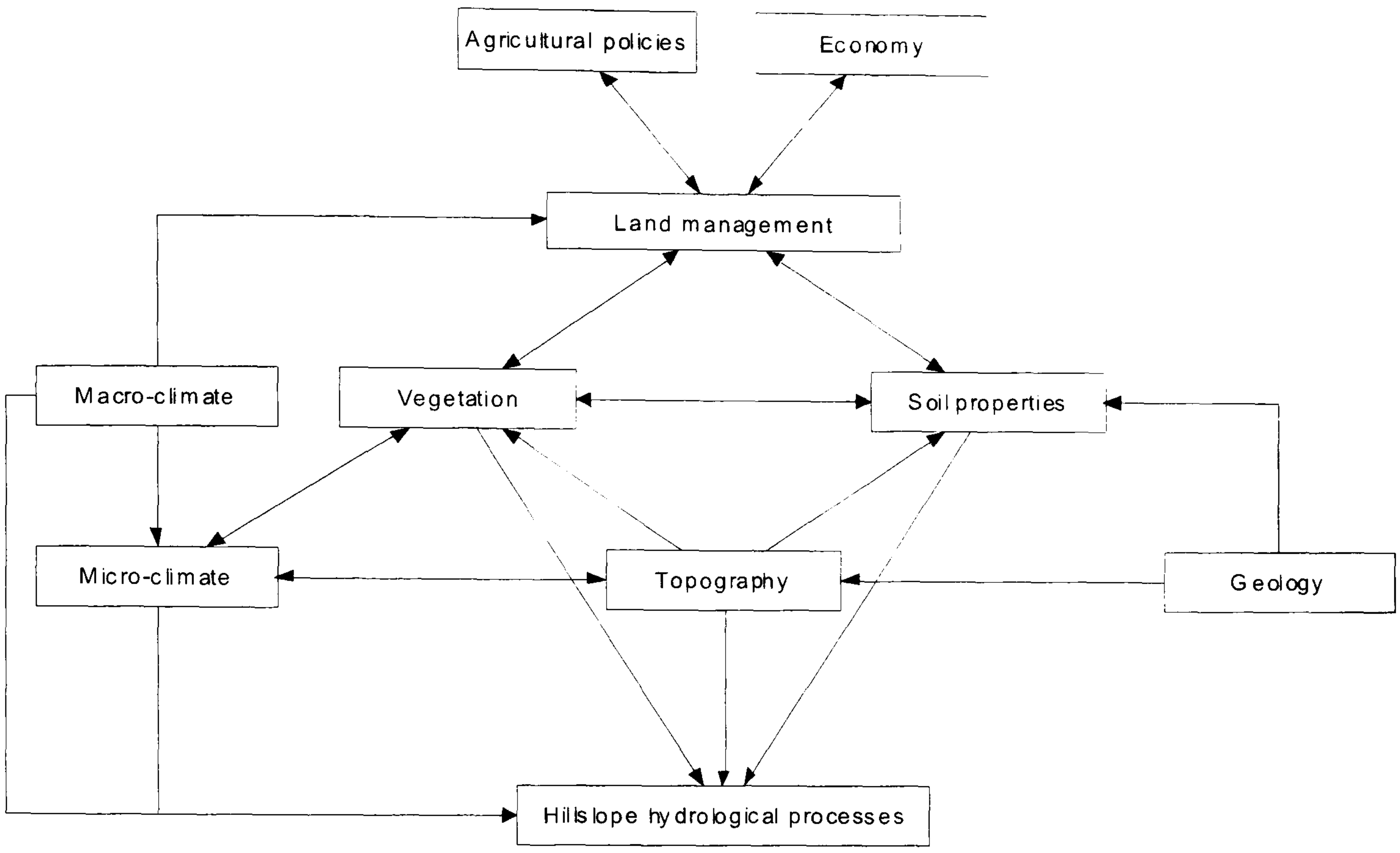


Figure 1.1: Conceptual model of the moorland hydrological system of Dartmoor.

Land management responds to agricultural policies and the economy, and is therefore also an important factor in the moorland hydrological system. Vegetation is altered by burning or by grazing livestock, which could also have consequences for the soil and hydrology. The conceptual model of the moorland system on Dartmoor, as shown in Figure 1.1, will be used in this thesis as a framework for explaining natural and man-induced influences on the hydrology.

1.2 Aims and objectives

This study aims to understand the hydrological response of a Dartmoor catchment by detailed investigation of the hillslope scale processes determining soil water movement. A particular aim of this research is also to establish how grazing and burning may affect the hillslope hydrological processes and their spatial and temporal variability.

As demonstrated in Section 1.1, hillslope hydrology is influenced by many different factors. It is of vital importance that the relative significance of the main soil hydrological pathways are recognised before an attempt can be made to estimate the effects of management on the hydrological system. Therefore, the aims will be subdivided into (i) a description of the fundamental baseline processes, in which the major hydrological processes will be investigated and (ii) the consideration of the land management impacts upon these processes. The objectives of the research are given below:

1. **Hydrological processes**

1.1 To study the hydrological behaviour of a Dartmoor stream. The hydrological processes determining the rainfall-runoff response at the catchment scale will be investigated;

1.2 To establish the relative importance of topography, soil physical characteristics and vegetation to soil moisture organisation at the plot and hillslope scale;

1.3 To investigate the role of soil moisture patterns at the hillslope scale in runoff generation.

2. **Land management**

2.1 To investigate the relationships between grazing densities and vegetation composition at the catchment scale;

2.2 To assess the influences of different grazing pressures on soil properties at the hillslope scale;

2.3 To examine the effects of heather burning on the soil and vegetation cover at the plot scale in order to estimate its influence on soil hydrology;

2.4 To consider the implications of the research results for grazing and burning management of the Holne Moor catchment and to extend the findings to other areas of the Dartmoor Commons.

1.3 Outline of the thesis

The thesis is structured following the main objectives. Chapter 2 provides a literature review as a context to this study, in which Fig. 1.1 is used as a framework. The chapter describes moorlands in Britain in general, and Dartmoor in particular in terms of climate, vegetation, soils and hydrology. The importance of soil properties to soil water movement is described at the plot scale. The chapter also presents a literature review on hydrology at the hillslope scale. Finally, land management of the moorland of Dartmoor is outlined.

Chapter 3 describes the study area on Holne Moor in more detail, but also presents a description of the Dartmoor area in general to provide a context of the environment in which this study was carried out.

In Chapter 4, the methodology and experimental set-up will be outlined and justified.

The remaining chapters follow the main objectives (Section 1.2). Chapter 5 details the hydrology of the watershed at catchment level (Objective 1.1). The main runoff-generating processes and soil water pathways are studied at this scale.

Chapter 6 focuses on the first aim, the major hydrological processes. The chapter describes the relationships and relative importance of the spatial variability of topography, soils and vegetation in relation to the hydrology at the hillslope scale (Objective 1.2). In the final section of this chapter, a conceptual model of hydrological pathways within the instrumented hillslope will be proposed (Objective 1.3).

Chapter 7 describes the complex relationships between vegetation cover and distribution, soils, topography and hydrology at the plot, hillslope and catchment scale to provide a context for Objectives 2.1 and 2.2.

Chapter 8 compiles the conclusions from Chapter 6 and 7 to study the objectives of the second aim, the influence of land management on hydrology (Objective 2.3 and 2.4). The relationships between all factors of the Dartmoor hydrological system are refined.

Chapter 9 synthesises the conclusions from the study and present recommendations for future land management and necessary research.

Chapter 2: The moorland environment

2.1 Introduction

After the introduction of Chapter 1, a more detailed literature study of the moorland environment is presented in this chapter. Also, the hydrology at plot and hillslope scale is described in general terms, to provide a background for this study. The chapter is structured as follows:

- In Section 2.2, a definition is given of moorland. Following this definition, the interaction between the different physical processes determining the hydrology is explained, in order to provide a context for this chapter.
- In Section 2.3, the major characteristics of British moorlands in general and Dartmoor in particular are described.
- Section 2.4 details the vegetation communities of Dartmoor and its relation to the Dartmoor environment.
- Section 2.5 reviews soil properties and hydrology at the plot scale in general, which may be applied to the Dartmoor area in this study.
- Section 2.6 subsequently scales up hydrological processes to the hillslope level, to give a background on hydrology in the light of the first aim (Section 1.2).
- In Section 2.7 and 2.8, the management aspects of grazing and burning and their influence on the physical processes and ultimately on the hydrology will be explained for the second aim. With reference to the moorland hydrological system as introduced in Chapter 1, all the individual processes and management influences, and their interactions are described.
- In Section 2.9 a brief background of agricultural policies and the economy of British hill and upland farming in the last century will be given to put the loss of heather moorland in perspective.

The moorland hydrological system as set out in Chapter 1 (Fig. 1.1) is used as a framework for the discussion in this chapter (Figure 2.1).

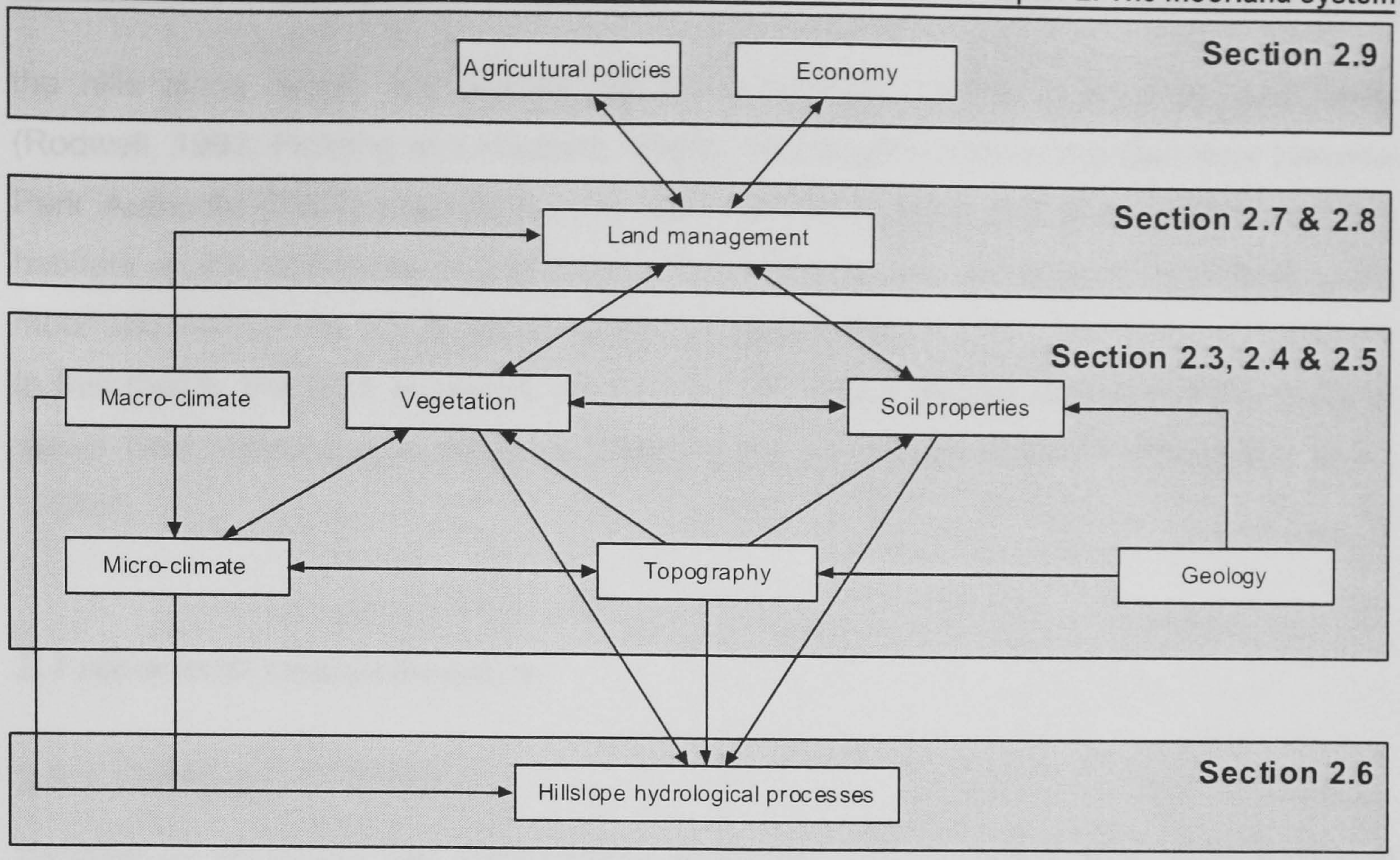


Figure 2.1: The moorland hydrological system.

2.2 The definition of moorland

The term 'moorland' usually refers either to shrubby heath or rough unenclosed grassland. However, because of the large variation in both environment and management across the country, a large number of different definitions of moorland exist. For example, the Land Utilisation Survey of Great Britain equated moorlands to heathlands, rough pasture and common land (Bardgett *et al.,* 1995). The Nature Conservancy Council (1984) described moorland as:

> 'uncultivated areas with short, rough vegetation, usually on poor soils, lying above the limits of arable land and enclosed pasture, but below the limits of natural tree-growth. They represent a sub-montane environment.'

Magnusson (1995) defined land above 250-300 metres with prevalent dwarf shrubs as upland heaths or moorland. Areas with 10% heather cover or more under 250-300 metres are classified as lowland heath. The Ministry of Agriculture, Fisheries and Food (Thompson *et al.*, 1995a) described moorland as

> 'land with predominantly semi-natural upland vegetation, or comprising predominantly rock outcrops and semi-natural upland vegetation, used primarily for rough grazing.'

The most comprehensive attempt to describe the moorland habitat from a more ecological viewpoint is the National Vegetation Classification (NVC). It describes 82 communities in the hills alone, which are divided into three habitats: heaths, grasslands, and mires (Rodwell, 1992; Fielding and Haworth, 1999). The English Nature and Dartmoor National Park Authority (1997) classification is more comprehensive and distinguishes five key habitats on the moorlands of Dartmoor: blanket bog, upland and lowland heathland, grass moor and valley mire, which are described in Section 2.4.

In this thesis, the term moorland will be used for rough grazing land above the limits of arable land and enclosed pastures, following the description of MAFF (Thompson *et al.*, 1995a).

2.3 Moorland characteristics

2.3.1 Moorlands in Britain

Heather on moorland has considerable economic, nature conservation and landscape value within Europe, especially Britain (Bardgett *et al.*, 1995; Thompson *et al.*, 1995a). The optimum environment for heather on moorlands is in the north and the east (Weaver *et al.*, 1998). Nevertheless, a variety of moorland environments occur throughout the country. Moorlands are most extensive in the Scottish uplands, but are also widespread in Northeast England, Northwest England, the West Midlands, North Wales, South Wales and Southwest England. They include amongst others the North York Moors, the Peak District, the Black Mountains, Snowdonia and the Brecon Beacons and usually occur on the higher grounds. In Southwest England they consist of Exmoor, Dartmoor and Bodmin Moor (Bardgett *et al.*, 1995; Thompson *et al.*, 1995b).

Virtually all of the British moorlands occur between the edge of enclosed agricultural ground (300 metres, depending on the geographical location) and the original climax upper tree line (about 600 m, also depending on position; Thompson *et al.*, 1995b). Recent land cover comparisons show that moorlands are unenclosed by definition, with soils having a peaty surface horizon (Bardgett *et al.*, 1995). The area corresponding with more than 1000 mm yr^{-1} of precipitation corresponds reasonably well with the British moorland extent (Thompson *et al.*, 1995b).

Although typified by very humid conditions, the different moorlands in Britain have distinctively different climates. In the north, moorland areas generally show lower temperatures, higher winds and larger precipitation amounts. A larger proportion of precipitation occurs in the form of snow than on the more southerly moors. Due to their southern location and their relatively low altitude, moorlands in Southwest England have a relatively mild climate (Gimingham, 1975). But because of its proximity to the Atlantic, rainfall amounts are relatively high. Due to these wetter and warmer conditions than moorlands elsewhere in Britain, heather species are at the limit of its growing conditions, resulting in a relatively high abundance of other species such as hardy grasses and bracken. Therefore, the moorland vegetation in the southwest shows a complex spatial mosaic of heath and grass-heath communities (Weaver *et al.*, 1998).

British moorlands have been maintained mainly by grazing and rotational burning over the last 150-200 years (Thompson *et al.*, 1995b). They have to be managed to prevent further succession (McTernan, 1993). Their main land use is extensive sheep grazing and grouse rearing on the more northern moors. In Scotland, the areas are managed mainly for Red Deer (Thompson *et al.*, 1995b).

Currently, many of the moorlands are designated as National Parks, Areas of Outstanding Natural Beauty, Sites of Specific Scientific Interest and Environmentally Sensitive Areas (McTernan, 1993).

2.3.2 Interactions between climate, vegetation, soils and hydrology on moorlands

Microclimatic conditions on moorlands at sub-catchment and hillslope-scale vary from location to location, due to altitude, slope and aspect (Fielding and Haworth, 1999). This causes spatial variation in the vegetation, soils and hydrology of moorlands.

Vegetation covers and protects the soil against climatic influences (Evans, 1996) and also influences the soil structure (Section 2.5). Precipitation on vegetated land is intercepted and temporarily held in the plant canopy. This water can either evaporate or drip off, if the rainfall exceeds the evaporation rate. Rainfall can either reach the soil surface by direct throughfall, or by indirect throughfall by the plant canopy or stemflow (Williams *et al.*, 1987; Wallace and Oliver, 1990). Vegetation and deep litter acts as a (temporary) storage of water before evaporation or infiltration and in this manner the vegetation regulates the water input to the soil surface (Chorley, 1978; Williams *et al.*, 1987; Church and Woo, 1990), indirectly affecting soil formation. The cover and the litter layer also prevent rapid drying out of the topsoil (Gimingham, 1975). The maintenance of infiltration capacity is directly influenced by root growth (Whipkey and Kirkby, 1978; Evans, 1996). Rooting of plants improves soil structure by the input of organic carbon, increasing permeability and decreasing runoff (Whipkey and Kirkby, 1978; Evans, 1996).

Seasonal changes in rainfall and evapotranspiration cause highly variable soil moisture regimes (Grayson *et al.,* 1997): in summer, the transpiration by the vegetation is higher, and rainfall lower, which results in lower soil moisture levels. During winter, transpiration declines virtually to zero, while precipitation increases, causing higher soil moisture levels (Western *et al.*, 1998). As a result, groundwater levels and subsurface fluxes will be higher, and also overland flow may occur more frequently (Shaw, 1994). Ultimately, stream discharges will be higher in winter.

2.4 Moorland vegetation and its relation to climate, soils and hydrology

In this section, typical moorland vegetation is described and related to its preferred climate, soil type and wetness. Also, the influence of vegetation types on the soil is outlined.

2.4.1 Heather species

Heather species (*Calluna vulgaris, Erica tetralix, Erica cinerea*) require a very specific climate. On moorlands, they occur mostly in a temperate, moist climate with mild winters (Gimingham, 1975). The mean temperature of the warmest month must not be higher than 22°C and at least four months need to have a mean temperature of above 10°C. The favourable climate can be described as oceanic, without temperature extremes, but with abundant (more than 1000 mm) and well-distributed rainfall over the year (115 rain days or more). A high humidity due to modest amounts of prolonged rain and relatively low evapotranspiration needs to be maintained (Gimingham, 1972; Fielding and Haworth, 1999). Although a maximum temperature is given here, the temperature itself is not a limiting factor. High temperatures induce high evaporation stress in heather species. The favourable climate is characterised by relatively long spring and autumn periods, the latter in favour of the heather species to harden the vegetation against winter. Additionally, it is very tolerant of considerable exposure to high winds (Gimingham, 1972).

Heather species are associated with acid soils (Fielding and Haworth, 1999). To a certain extend, the species grow in both wet and dry conditions (Gimingham, 1975) and the extent to which soil conditions are favourable for the dominant species depends mostly on the moisture content (Fielding and Haworth, 1999). *Erica tetralix*, for example, mostly occurs on bogs and peaty waterlogged moors. *Erica cinerea* prefers drier, better-drained mineral soils (Gimingham, 1975; Perring and Walters, 1989). Both *Erica*-species are often found close together, which reflects the subtle interaction between surface topography and wetness (Fielding and Haworth, 1999).

A litter layer under heather species only starts building up after a few years of growth (Gimingham, 1972). This layer can be of importance in (temporarily) storing water and vertical water movement, having a large influence on the soil water status. Not much is known about interception and water storage in the litter layer. However, the effect of heather species on rainfall and percolation is much less seasonally dependent than other vegetation species like the grasses and bracken (Williams *et al.*, 1987).

The rooting depth of heather species can reach up to one metre in free draining soils, but in more leached podzols the roots do not tend to grow deeper than the top of the A2 horizon. On an English wet heath, Rutter (1955) showed, that 80% of the *Calluna vulgaris* roots are found in the top 13 cm of the humus-rich topsoil and are virtually absent in the mineral subsoil with little humus. Chapman (1967) found the biomass of the roots of, amongst others, *Calluna vulgaris*, *Erica cinerea* and *Erica tetralix* to be concentrated in the top 20 cm in a sandy soil.

However, heather species are often associated with the podzolisation process, and the species have a distinct effect on the development of podzols, sometimes resulting in the formation of a thin ironpan (Gimingham, 1975). The ironpan sometimes impedes water in such a way, that the environment becomes favourable for peat growth, altering the soil significantly (Gimingham, 1975). Also, this horizon can prevent most plant roots from growing deeper and a dense horizontal layer of roots develops above the barrier (Gimingham, 1975). This horizontal root growth can have important implications for soil structure and soil water movement.

The heather community is dependent on burning and grazing management (Gimingham, 1975; Weaver *et al.*, 1998). Heather has been maintained because it provides a valuable food resource in the grazing system for sheep on soils that could not support productive grasslands. It is heavily grazed in winter when grasses are diminished, but sheep may also return to heather in late summer, as the young shoots of the current year are still edible but when the grasses are mostly dried out (McTernan, 1993). The effect of regular and controlled burning is to give the species a competitive advantage over other plants by providing a warm seed bed and to rejuvenate without substantial competition (McTernan, 1993).

The environment for *Calluna* to regenerate is most favourable after a burn (Gimingham, 1975). *Calluna* seedlings require a fluctuating temperature and exposure to light, two conditions that meet the environment left after a fire. These bare areas are warmed up quickly during the day by the sunlight and cool down rapidly at night by radiation from the surface. The fire itself may act as a stimulant as well in the germination of *Calluna* seedlings, as they are exposed to a short increase in temperature during the fire (Gimingham, 1975).

The process of succession after a fire will first provide colonisers like bilberry (*Vaccinium myrtillus*), grasses (McTernan, 1993), mosses and lichens (Gimingham, 1975). After ten years, *Calluna* will be taking over. After 20 years, it reaches its mature stage. It then out-competes the other plants for nutrients, water and light. If it is not managed at this stage, the period of dominance will be short and bracken (*Pteridium aquilinum*) takes over as the *Calluna* degenerates (McTernan, 1993). Preferably, the heather should be burned in this stage, to prevent further succession (Gimingham, 1975).

2.4.2 Gorse

Gorse (*Ulex galii*) in association with *Agrostis curtisii* is common in South and Southwest England (Fielding and Haworth, 1999), and by some authors is regarded as typically growing in lowland heathlands (Gimingham, 1975). It grows typically in association with *Calluna* and *Erica cinerea* and thrives in a mild oceanic climate on acidic grasslands (Perring and Walters, 1989). The species can be subdivided into two sub species, *Ulex europaeus* and *Ulex minor*. *Ulex europaeus* is much more widespread throughout the UK, but to a much lesser extent world-wide (Ratcliffe and Thompson, 1988).

Although the occurrence of gorse is not as widespread as heather species, it can be of importance from a management perspective. *Ulex* spp. sometimes grows in clusters with *Calluna*, providing protection against grazing animals (Shepherd, 1998, pers. comm.). As gorse often grows in relatively dense shrubs, it can induce much higher temperatures for a longer period than other vegetation species during burns (Gimingham, 1975), and may therefore have a more profound effect on soil properties and the hydrology.

2.4.3 Grasses

The grass moors reflect a greater degree of human influence than heather dwarf shrubs. Although many of the grass species (Section 2.4.1) also occur in mainland Europe, the vegetation associations are different (Ratcliffe and Thompson, 1988).

Agrostis spp. mainly grow on poor, drier acid soils, particularly on steep slopes. *Festuca* can be found on well-drained, nutrient poor soils (Hubbard, 1984, Fielding and Haworth, 1999). Both species mainly root in the top 20 cm of the soil (Gimingham *et al.,* 1979). *Nardus stricta* is usually associated with *Calluna* stands (Weaver *et al.*, 1998). Its coverage generally increases with increased grazing pressure, as sheep prefer the heather species above *N. stricta* (Kent and Wathern, 1980; Armstrong and Milne, 1995). *Molinia* is mostly found on heathlands in Southwest England and Wales. It mostly grows on peaty, very wet but not waterlogged soils. It creates a thick litter layer in large tussocks that can suppress other species (Rutter, 1955; Fielding and Haworth, 1999). This litter layer can play an important role in the storage and transport of water. The rooting depth of *Molinia* in deep peat is largely in the 15-30 cm area (Gimingham, 1975), but on sands, 92% of all roots between 0 and 40 cm depth were found in the top 20 cm (Chapman, 1967). It has been shown, that improved aeration of waterlogged soils can cause the spread of *Molinia* (Rutter, 1955). Also, burning of heather gives *Molinia* a competitive advantage (English Nature, 2001).

Molinia has been mostly associated with the growing grazing pressures since the 1800s, as the species is highly unpalatable for sheep and hence it could spread without suppression (Fielding and Haworth, 1999). Cattle and sheep prefer *Agrostis* spp. and *Festuca* spp., as these species have a higher nutrition value (Gimingham, 1972; Fielding and Haworth, 1999). Cattle do seem to graze *Molinia* however, and are able in places to suppress it (Fielding and Haworth, 1999).

2.4.4 Bracken

Bracken *(Pteridium aquilinum)* is associated with high grazing levels and areas with nutrients export due to grazing (Section 2.4.1). The species is spreading throughout Britain in heaths and grasslands, usually on acid soils and on sheltered parts of hills.

Bracken rhizomes have a large impact on the lateral permeability of the soil. As it is a travelling geophyte (Gimingham, 1975), it advances forward, the rear roots die back and large, horizontal cracks are left in the soil (Arnett, 1976) at about 10 to 30 cm depth. Bracken regulates rainwater down to the soil surface to a large extent, depending on season (Williams *et al.,* 1987). In summer, when the bracken is fully grown, the vegetation intercepts large amounts of up to 100% of rainfall whereas in winter, when it has died back, there is no canopy left to intercept. This interception is highly dependent on the rain intensity, with most interception during storm of low intensity. Annually, about 20% is intercepted. The litter layer, which is at its maximum thickness in autumn, also regulates much of the rainwater (Williams *et al.,* 1987).

Livestock avoid *Pteridium* because it is poisonous and it is not affected by fire, as reproduction occurs by its rhizomes (Gimingham, 1975). The spread of bracken may be halted by cattle trampling or mowing in spring but can only be controlled by chemical sprays (Gimingham, 1975; Phillips, 1980; Ratcliffe and Thompson, 1988).

2.5 Soil properties and soil water movement

It has been shown in the previous section, that soil wetness, especially of the topsoil, is one important factor for the growing environment of plant species and habitats of Dartmoor. Not only is soil moisture distribution important in determining the occurrence of habitats, but in turn it is also a result of the presence of vegetation species. The spatial variation of soil moisture content can also provide important insight into redistribution processes of soil water (Grayson *et al.*, 1997) and therefore soil and hillslope hydrology. It is a major factor in hillslope hydrological studies (Western *et al.*, 1999).

Trampling of or intensive mechanical pressure on the soil has been found to alter bulk density and pore size distribution (Ferrero, 1994; Proffitt *et al.,* 1995; Droogers, 1997) therefore altering infiltration rates, water storage (Dreccer and Lavado, 1993; Greenwood *et al.,* 1998) and consequently, soil moisture content.

Hence, it is necessary to understand the importance of topsoil properties to soil moisture and the hydrology to achieve part of the first objective (Chapter 1). The following sections therefore outline the interactions between soil structure, porosity and soil water fluxes.

2.5.1 Soil structure

Structure of the soil was described by Brewer (1964) as:

> "The physical constitution of a soil material as expressed by size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves."

There is no generally accepted classification of soil structure, but it can be described in terms of permeability, bulk density, organic matter, infiltration rate, penetration resistance, porosity and pore-size distribution (Koorevaar *et al.*, 1983; Droogers, 1997). Organic matter and clay particles in soils bind mineral particles together forming aggregates, enhancing soil structure and increasing water retention, infiltration, drainage, soil temperature, air transport and root penetration (Koorevaar *et al.*, 1983). The dependence of water flow on soil structure is described in the following sections.

2.5.2 Water flow through a soil

Water movement through homogeneous soils can be described in terms of steady saturated flow, steady unsaturated flow and nonsteady unsaturated flow (Koorevaar *et al.*, 1983). Water movement through a soil is driven by the hydraulic potential H (cm), which is a function of the pressure head h (soil suction or negative soil pressure; cm) and the gravitational potential or height above a reference level z (cm; Koorevaar *et al.,* 1983; Hendrickx, 1990; Equation 2.1):

[2.1] $$H = h + z$$

In steady saturated flow, the water flux q (cm s^{-1}), hydraulic conductivity K (cm s^{-1}) and volumetric soil moisture content θ (cm^3 cm^{-3}) are constant through time and space, and θ equals the total porosity of the soil (Koorevaar *et al.,* 1983). Darcy's law describes the water flux through a one-dimensional, saturated vertical column in a mathematical way as a function of saturated hydraulic conductivity (K_{sat}), H and z (Hendrickx, 1990):

[2.2] $$q = -K_{sat} \frac{dH}{dz}$$

In sloping areas, steady saturated flow through soils can also be described with Darcy's law. If the slope is relatively high in comparison to dH/dz, so that the groundwater table gradient (dz/dx, where dx is horizontal distance) can be assumed to be equal to slope α, the equation can be rewritten as (Church and Woo, 1990):

[2.3] $$q = K_{sat}\, d \sin\alpha$$

where d is the depth of the saturated zone.

In steady unsaturated flow, q is constant through time and space, but the hydraulic conductivity K and soil moisture content θ vary only in time. θ is lower than the total porosity of the soil, so not all pores are filled with water. It is found experimentally, that Darcy's law is still valid for unsaturated soils. In that case, K is replaced by the hydraulic conductivity dependent on the soil moisture content, $K(\theta)$:

[2.4] $$q = -K(\theta)\ \frac{dH}{dz}$$

This hydraulic conductivity is lower than the saturated hydraulic conductivity, because only pores filled with water can contribute to the flow (Koorevaar *et al.,* 1983; Kutílek and Nielsen, 1994). Empty pores act as a barrier to moving water in the soil (Gilman and Newson, 1980).

In non-steady unsaturated flow, q, $K(\theta)$ and θ vary in time and space (Koorevaar *et al.,* 1983). In reality, steady processes are rare and non-steady processes and events like rainfall, (evapo) transpiration and drainage mostly determine water flow through the soil profile. In the field, insight into non-steady flow processes can be obtained by analysing the soil suction in the soil profile through depth (Koorevaar *et al.,* 1983).

Thus, the relationship between hydraulic conductivity and water filled porosity needs to be understood when studying water flow through the soil profile. In the next sections, the porosity of the soil and the importance of pore size distributions to water flow are described in more detail.

2.5.3 Soil porosity

Total soil porosity Φ (cm^3 cm^{-3}) is defined as the volume of pores V_p (cm^3) in relation to the total bulk volume of the soil V_t (cm^3) (Koorevaar *et al.,* 1983; Kutílek and Nielsen, 1994):

[2.5] $$\phi = \frac{V_p}{V_t}$$

The total porosity is dependent on texture, bulk density, compaction and structure, and therefore on faunal and other biological influences (Droogers, 1997). In general, soil porosity can range from 0.4 to 0.6 cm^3 cm^{-3} in mineral soils to more than 0.9 cm^3 cm^{-3} in organic soils (Kutílek and Nielsen, 1994).

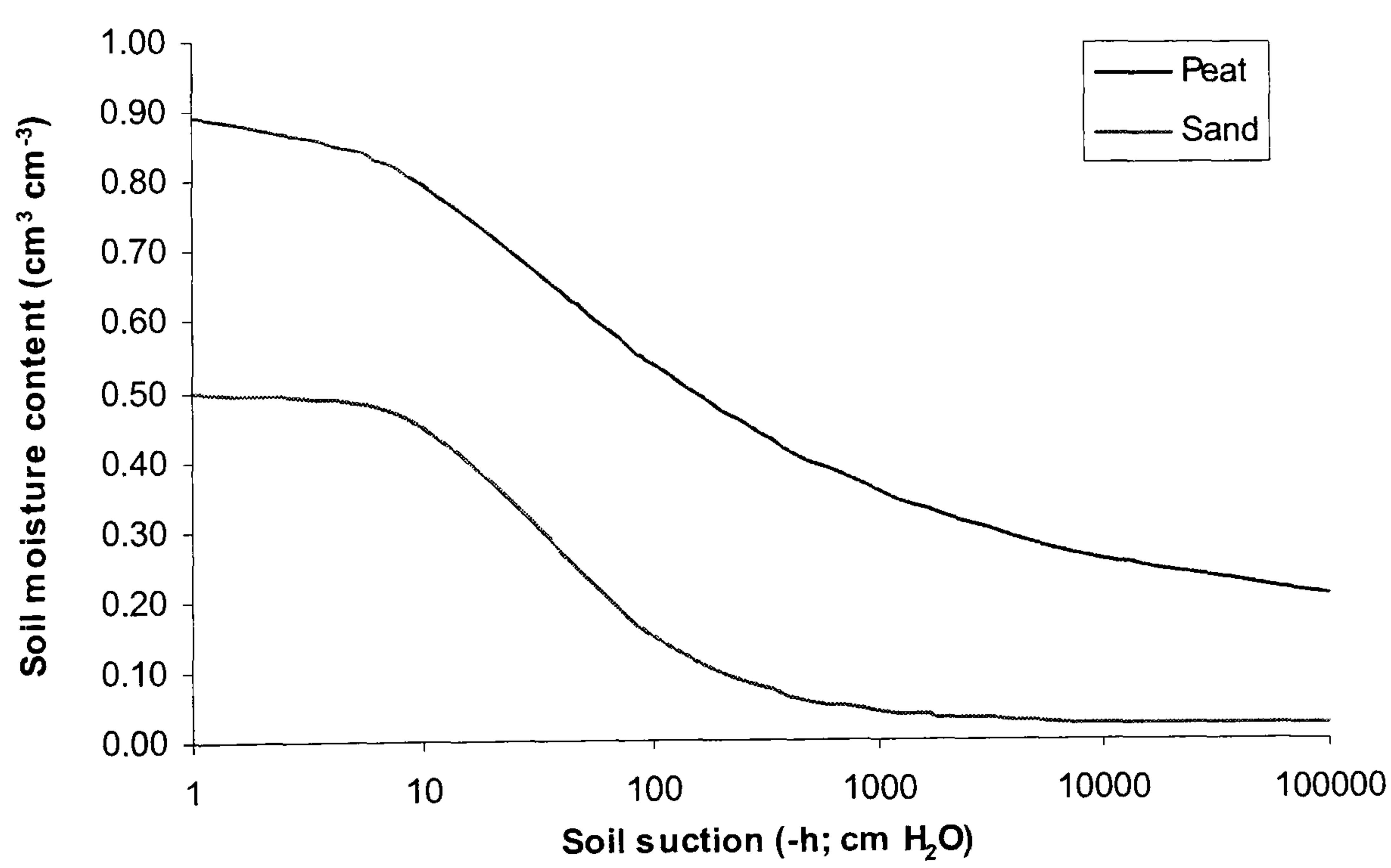


Figure 2.2: Example of a water retention curve of a peat and a sandy soil (after Weiss et al., 1998).

The pressure head h retains the water in pores in the soils. When the suction increases (or, in other words, the pressure head decreases), the pores are emptied, the larger ones first. This is an important phenomenon for hydrodynamic studies, as the pore size determines the flow of water and flux (Section 2.7.4). However, water storage and permeability are not a function of total porosity itself, but depend on the pore-size distribution (Kutílek and Nielsen, 1994). As different pore sizes retain water at different suctions, a water retention curve, a relation between pressure head and soil moisture content, can be created (Kutílek and Nielsen, 1994). This curve gives an estimate of the pore size distribution (Figure 2.2).

The classification of pores is based in the first instance on hydrostatic behaviour (Kutílek and Nielsen, 1994), but has consequences for the hydrodynamic behaviour of the soil. Definitions in pore sizes differ significantly. Macropores are defined by Koorevaar *et al.* (1983) as larger than 100 μm in diameter, mesopores between 30-100 μm and micropores smaller than 30 μm. Greenland (1977), Beven and Germann (1982) and Rowell (1994) regard pores larger than 50 μm as macropores or transmission pores. Between 0.2 and 50 μm (Rowell, 1994) or 0.5 to 50 μm (Greenland, 1977) they are termed storage pores. Macropores only conduct water at (near) saturation. Transmission and mesopores are the most important for water movement at non-saturation, since flow is a function of the radius of the pore (Section 2.5.4). In storage or micropores water is retained at greater suctions due to capillary forces.

Peat or peaty soils, which take up a large proportion of the soils on Dartmoor, are characterised by a large proportion of relatively small pores (Päivänen, 1973) and a very heterogeneous pore structure, originating from the original plant structure (Weiss *et al.,* 1998). Total porosity determines bulk density, but differences in plant residue cell structure and layering of the plant material from which the peat was derived determines the pore size distribution (Weiss *et al.,* 1998). Peat becomes increasingly compressed deeper in the profile, affecting the porosity and bulk density of the material (Zeeb and Hemond, 1998). Also, peats are known in dry conditions to shrink, leaving large desiccation cracks. These cracks can be regarded as large macropores, which can conduct water in very wet conditions, inducing so-called pipeflow (Gilman and Newson, 1980; Newson, 1997).

2.5.4 Pore sizes and soil water movement

Hydraulic conductivity in a tube is proportional to the square root of the radius of the capillary pore, which is derived from Poiseuille's law (Koorevaar *et al.,* 1983):

[2.6]
$$Q = -\frac{\pi r^4}{8\eta}\frac{\partial p_h}{\partial s}$$

where:

$\partial p_h/\partial s$ = the driving force divided by volume;

η = the water viscosity.

From this equation, the relation between hydraulic conductivity, soil moisture content and pore diameter can be established by:

[2.7]
$$K = \frac{1}{8\eta\tau}\Sigma(\Delta\theta)_i r_i^2$$

where:

i = pore size class;

r = pore diameter;

τ = a tortuosity factor.

From Equation 2.6 and 2.7 it can be deduced, that the largest pores attribute most to the flow of water, but also that the largest pores empty first when the soil becomes unsaturated (Figure 2.2). $K(\theta)$ therefore decreases sharply with soil moisture content (Kutílek and Nielsen, 1994).

In general, coarser textured soils have larger pores and therefore, sandy soils can conduct water quickly when close to saturation. Clay soils on the contrary, can store water for a long period of time, whereas conductivity is low (Koorevaar *et al.*, 1983). In terms of soil water movement, peats can behave distinctively different from mineral soils, because of the distinctively different pore size distributions (Hoag and Price, 1995; Zeeb and Hemond, 1998). Although the principle of soil physics is the same, many pores are dead-ended, or completely isolated, whereas others are open and connected (Weiss *et al.*, 1998). The difference pore size distribution depends on plant material, but also on the amount of peat in relation to the mineral soil content, which could be of importance for hydraulic conductivity values on Dartmoor.

2.5.5 Macropore and matrix flow

Two major flow paths in the unsaturated zone of the soil profile are generally identified: Macropore flow and micropore (or matrix) flow (Ratcliffe *et al.*, 1996). Micropores retain water by capillary forces (Section 2.5.4). Water through these pores (matrix flow) moves very slowly and is considered to be laminar (Kutílek and Nielsen, 1994).

Macropores (Section 2.5.3) are important flow routes. In these pores, capillary forces play an insignificant role. In situations in which the soil water pressure is positive or when an unsaturated soil is ponded, water flows through these macropores, either as a thick film along the walls, or as turbulent flow filling the entire pore (Kutílek and Nielsen, 1994). Macropores can be a very important rapid water transport route. Water movement through these pores can be simplified into three different stages (Beven and Germann, 1982):

1. Precipitation intensity is smaller than matrix infiltration. In this stage, all water input will be absorbed by the micropores connected to the soil surface, and no (rapid) macropore flow takes place;
2. Precipitation intensity is larger than matrix infiltration, but smaller than seepage into the macropores from the soil surface. In this stage, small-scale runoff may take place and both micropores and macropores are taking up large amounts of water. Water is flowing into the macropores along the walls and is infiltrating laterally into the matrix;
3. Precipitation intensity is larger than surface infiltration and seepage into macropores. Flow through the macropores is widespread. Water is stored on the soil surface or induces overland flow.

The different stages show, that besides precipitation intensity and infiltration capacity, the wetness of the soil is a major influence on the soil water pathway. Not only the general wetness is important, but also the wetness distribution plays a significant role. Stage two and three are situations in which Darcy's law cannot be used to assess infiltration, as his law requires a homogeneous soil. In these situations fluxes differ significantly within very short distances (Beven and Germann, 1982), and this heterogeneity has implications for the representative volume for measuring hydraulic conductivity.

Macropores can be subdivided into pores formed by soil fauna, roots formed by plant roots, cracks and fissures and natural soil pipes, formed by subsurface erosion (Beven and Germann, 1982; Kutílek and Nielsen, 1994; Newson, 1997) or desiccation (Gilman and Newson, 1980). The nature of the macropores is important, because this of influence to the connectivity of the pores. If macropores are connected, they can be hydrologically active over a longer distance. Therefore, methods that measure macroporosity alone are not adequate enough for hydrologic processes studies (Beven and Germann, 1982; Germann, 1990).

Macropore flow has been found in many studies, varying from heavy cracking clays (*e.g.* Robinson and Beven, 1983) to peats wherein large macropores (pipes) have been found due to desiccation in exceptional dry summers, which conducted high amounts of runoff during rain events (Gilman and Newson, 1980; Jones and Crane, 1984). In the latter studies, flow through pipes has been found to play an important role in water routing through peaty podzolic soils in the Wye catchment in Wales, UK. Although this study was carried out in an exceptionally dry summer, this form of transport was expected to be very important in that region, and could be of importance in all upland areas throughout Britain (Gilman and Newson, 1980), including Dartmoor.

2.6 Hillslope hydrological processes

The relative importance of the different soil water pathways is not only a function of wetness conditions (previous section), but also of local topography, soils and vegetation. In order to understand the hydrological behaviour of a watershed, the relative importance of soil water pathways under different conditions has to be studied at the hillslope scale. Therefore, the following sections describe:

- storm runoff generating mechanisms (Section 2.6.1).
- the importance of topography to soil water movement (Section 2.6.2);
- the importance of soil moisture to soil water movement (Section 2.6.3);

2.6.1 Main runoff generating processes at the hillslope scale

Overland flow, subsurface flow and groundwater flow are the main water pathways to a stream (Chorley, 1978; Anderson and Burt, 1990a). Groundwater flow can be regarded as flow through bedrock (*e.g.* deep groundwater aquifers) and is relatively slow. Subsurface flow is unsaturated or saturated flow in the near surface soil or regolith above the groundwater level (Kirkby, 1988). Overland flow is the transport of water across the soil surface, either caused by infiltration excess or induced by saturation of the (top) soil (Chorley, 1978; Anderson and Burt, 1990a). Subsurface and overland flow are usually regarded as storm flow, and are much quicker than groundwater flow (Anderson and Burt, 1990b). The main runoff generating processes at the hillslope scale are discussed below. The typical pathways as found on Dartmoor, studied by Williams *et al.* (1984) are described in Chapter 3.

Overland flow

Infiltration excess overland flow occurs when the rainfall intensity exceeds the infiltration capacity of the soil. It was first described by Horton (1933) and is therefore also called Hortonian overland flow. Although at first widely accepted as an important stormflow generating process, it is rarely observed in temperate regions (Kirkby, 1978; Anderson and Burt, 1990a). A second form of flow across the surface, saturation overland flow, is produced when rain falls on a soil which is saturated near the soil surface. The water cannot infiltrate and therefore occurs as overland flow (Kirkby, 1978; Anderson and Burt, 1990a).

Subsurface flow

Although Horton's theory from 1933 suggests that the only source of storm runoff was the excess of water unable to infiltrate into the soil ('infiltration excess overland flow'), subsurface runoff is now being regarded as the driving force in runoff generation (Kirkby, 1988; Anderson and Burt, 1990b).

In a literature review of hillslope process studies, Anderson and Burt (1990a) describe subsurface flow as comprising macropore flow, pipeflow and/or soil matrix flow, in which macropore flow and pipeflow are the most rapid.

It has now been widely accepted that stormflow is often conducted through structural openings, root channels or animal burrows and thereby bypasses the soil matrix as macropore flow (Section 2.5.5; Beven and Germann, 1982; McDonnell, 1990) and sometimes as pipe flow (Anderson and Burt, 1982; Jones and Crane, 1984). Velocities associated with this form of water transport can be orders of magnitude greater than flow through the soil matrix (Gilman and Newson, 1980; Church and Woo, 1990; McDonnell, 1990). In this way, much higher velocities than the saturated hydraulic conductivity can be achieved. These conductivities are often deduced from laboratory experiments, with a relatively low sample volume and a possible destruction of the original soil structure (Williams *et al.*, 2002).

Gilman and Newson (1980) showed that in the Cerrig yr Wyn catchment, velocities associated with pipeflow were typically in the order of 0.1 m s^{-1} (360 m h^{-1}) on slopes of more than 10°. McCaig (1980) showed similar velocities between 0.01 and 0.1 m s^{-1} in a small headwater catchment on a wet moorland in Yorkshire. He also showed, that a certain soil moisture threshold was needed to induce pipeflow.

Because of its slow nature, soil matrix flow (Section 2.5.5) can only attribute to the storm runoff if this pathway is sufficiently close to the stream, the soil hydraulic conductivity of the topsoil is high and when an impermeable or saturated layer at depth exists in order to enable lateral subsurface flow (Anderson and Burt, 1990a).

Flow from the variable source area

Hewlett and Hibbert (1967) described flow from the variable source area, called the partial area concept by Dunne and Black (1970). This concept assumes that a small portion of the catchment mainly generates the storm runoff. Rainfall on the hillslope forces out the water present at depth and at the base of the slope. When this flow exceeds the soil transmissivity capacity, the water will occur at the surface as return flow, with saturated soils near the stream as a result. The saturated area at the base is called the variable source area and conducts the water to the stream. The main difference between the partial area model and the variable source area model is the process which is responsible for the transport of water from the source area to the stream. The partial area model assumes infiltration excess overland flow, whereas the variable source area model is explained by saturated overland flow and subsurface storm flow (Anderson and Burt, 1990a).

The contributing area is more or less constant in extent during most storms, but in large storms, they expand from valley floors to the lower hillslopes. In these expanded areas, overland flow is also the main contributing factor, and subsurface runoff is apparent but relatively small (Dunne and Black, 1970). The variable source area concept suggests that rainfall amount and intensity are the controlling factors in storm runoff (Dunne and Black, 1970).

New and old water

In many studies, subsurface flow accounted for much of the stormflow, although it is often not clear how these processes occur (Anderson and Burt, 1990b). According to macropore theory, flow through such pores is sufficiently fast to contribute to stormflow. During this time, the water has insufficient time to interchange with the soil matrix. This results in water, which is isotopically and/or chemically different from soil water that has been in the soil profile for longer. A distinction between 'new' (rain event) and 'old' (pre-rain event) water has therefore been established. The different water signatures can be measured in the stream, giving a measure of the contributions of both new and old water to the storm flow (Germann, 1990).

If most of the stormflow has been accounted for through macropores, it is to be expected that water exfiltrating at the bottom of the hillslopes consists of a large proportion of new water (Anderson and Burt, 1990b, Germann, 1990, McDonnell, 1990). However, this is often not the case. Several researchers found conflicting results. Different researchers have shown that macropore subsurface flow can be an important factor (*e.g.* Mosley, 1979; Robinson and Beven, 1983; Robinson *et al.*, 1987), but analysis at the hillslope scale has shown that quite often, this water can be regarded as old water. This implies that this water has been in the profile for a relatively long time (Pearce *et al.*, 1986; Brammer and McDonnell, 1996). Many researchers have tried to explain this inconsistency with various hydrological mechanisms (Williams *et al.*, 2002).

Pressure waves

A possible explanation of rapid responses at the hillslope scale combined with large old water proportion of the storm flow could be given by the results of Rasmussen *et al.* (2000). They described so-called pressure waves with the use of a laboratory tracer experiment on an intact saprolite core. On this core, which was kept at near-saturation, a chloride tracer and flush water was added with an intermittent spray system, to monitor the breakthrough curve of the tracer at the bottom of the core. Tensiometers, installed at two depths within the core, showed an immediate response to the application of the water. This response was about 1000 times faster than the applied water in terms of head and travelled through the core at a velocity of up to 1.5 m hr^{-1}. This pressure wave propagated through the core and expelled some water from the bottom. The tracer moved through the core at a much lower velocity, associated with the hydraulic conductivity, with the first appearance of chloride 1.25 days after application. The core responded to the change in water storage in the soil matrix as a reaction to the applied water.

2.6.2 Hydrology in relation to topography

Water movement in the unsaturated zone is a function of hydraulic gradient and therefore, the gradient of the slope determines the speed with which the water moves downward. In other words, redistribution of soil water and flow rates are slowest in regions with the lowest slope gradients (Knapp, 1978). As a consequence, soil moisture contents are often greatest on the plateaux and at the base of the slopes (Anderson and Burt, 1978; Knapp, 1978; Whipkey and Kirkby, 1978; Church and Woo, 1990).

The slope profile is also a very important factor in flow rates. Hillslopes often have a convex- (straight-) concave profile (Knapp, 1978; Whipkey and Kirkby, 1978; Church and Woo, 1990), inducing different fluxes at different locations. In the convex areas between plateaux and the steepest area of the slope, subsurface flow is diverging, as water movement is in the direction of the highest hydraulic gradient. Water moving laterally downslope in these areas causes relatively low soil moisture contents. Around concavities however, subsurface flow is converging. In these zones, water accumulating from steeper parts produces higher soil moisture levels, and may even cause overland flow (Knapp, 1978; Whipkey and Kirkby, 1978). The relative increase in soil moisture content increases with distance from the water divide, which is directly related to the water amount accumulated from upslope (Whipkey and Kirkby, 1978; Church and Woo, 1990).

The combination of the slope shape and the distance to the water divide determines the upslope contributing area. Areas with a large upslope contributing area receive relatively high amounts of water, causing higher soil moisture levels and become saturated more quickly than surrounding areas (Whipkey and Kirkby, 1978, Beven, 1997). Therefore, concavities are more likely to induce overland flow (Whipkey and Kirkby, 1978).

Kirkby (1975) combined the upslope contributing area (*a*) and local slope angle (β) into a simple topographic index to describe water movement (Section 4.6.1). The index can be regarded as a measure of hydrological similarity (Beven, 1997). High index values generally saturate first and could indicate potential (sub) surface contributing areas. Such areas are therefore of more hydrological importance to runoff generation than areas with a lower index value (Beven, 1997).

The soil water movement as described above only exists in the ideal situation of homogeneous soil conditions. However, this is often not the case and soils vary considerably on hillslopes, affecting soil water movements considerably (Crave and Gascuel-Odoux, 1997). The topographic index can therefore be adjusted by adding a soil conductivity parameter (Quinn *et al.*, 1995). On gentle slopes, soils tend to be deeper and better structured which may increase their water holding capacity (Knapp, 1978). Both topography and soil variability therefore are important factors in flow rate determinations on hillslopes.

An indirect influence of topography on the hydrology on the hillslope is aspect, which influences the amount of precipitation on a certain area (Church and Woo, 1990).

At landscape scale, topography can be an important indication of flow mechanisms on hillslopes. The mosaic of different slope angles, aspect, slope profiles, contributing areas and soils determine the local water transport and therefore need to be taken into consideration when studying hillslope hydrological processes.

2.6.3 Soil moisture and hillslope hydrology

All flow processes presented in the previous sections were shown to be dependent on both topography and antecedent moisture conditions. Subsurface flow rates are highest in areas with high moisture contents, which are hillslope hollows, at the base of slopes (increased contributing area combined with decreased slope) and in areas of reduced soil moisture storage (Whipkey and Kirkby, 1978). Three zones may be identified where high soil moisture contents are most likely to occur (Anderson and Burt, 1990b):

1. Hillslope hollows (converging flowlines);
2. At the base of the slope because of increasing drainage areas upslope;
3. In areas of reduced soil moisture storage.

Western *et al.* (1999) described the organisation of soil moisture in temperate Australia at the catchment scale. They showed that during wet periods, soil moisture patterns were more uniform, showing large spatially interconnected areas. Grayson *et al.* (1997), describing the same catchment, explained the two different states in terms of local and non-local controls. In dry conditions, soil moisture is mainly determined by vertical (local) flow, controlled primarily by evapotranspiration from the vegetation and soil. In sufficiently wet conditions, the hydraulic conductivity increases and soil water is enabled to move laterally, determined by topography, forming a much more homogeneous moisture pattern on hillslope scale and could therefore be described as non-local.

The importance of wetness conditions show, that soil moisture contents are of vital importance in studying hydrology at the hillslope scale.

2.7 Grazing management

The long history of moorland management, often changing through time and space, resulted in a dynamic equilibrium, which is constantly adapting to changing management influences. Unfortunately, due to the common grazing over large, unenclosed areas, little or no data are available on land management in terms of the frequency and intensity of grazing on Dartmoor in general (Havinden and Wilkinson, 1970) and in the study catchment in particular (Goodfellow, 1998, pers. comm.). It is therefore difficult to establish a causal relationship between vegetation characteristics and grazing behaviour of livestock.

Although the internal controls of this moorland equilibrium are not very well known, within the framework of this research it is the resulting vegetation mosaic due to grazing management that is most important.

In order to understand grazing impacts on hydrology, there is a need to assess the effect on soil properties by different stocking densities, either directly by trampling (soil compaction) or indirectly by altered vegetation composition (Second aim; Chapter 1). The influence of vegetation on soils is described in Section 2.4. This section describes the use of grazing as a management tool, and the impacts of grazing on the environment. The section is structured as follows:

- In Section 2.7.2, the grazing behaviour of animals, especially sheep, and their interrelation with the vegetation is explained from the literature.
- In Section 2.7.3, the effects of grazing densities of vegetation composition is outlined, as this can be an important aid in assessing densities in grazed areas where no data of livestock numbers are available, as on most Dartmoor Commons.

- In Section 2.7.4, the impacts of trampling on soil properties and hydrology are described.

2.7.1 The grazing behaviour of livestock

In general, livestock are attracted to areas with more nutritious vegetation and as a consequence change plant communities by selective removal of different species (Evans, 1997) and by faecal deposition (Hester and Baillie, 1998), resulting in variable vegetation mosaics.

The spatial distribution of vegetation is a very important factor in grazing behaviour (Hester and Baillie, 1998). Sheep are very selective in choosing the most palatable species (Gimingham, 1972), and therefore livestock will prefer certain areas above others, resulting in a high degree of grazing heterogeneity, with increased grazing levels at some locations, and decreased at others (Welch, 1984a). Due to grazing, the species composition is changing, not only by selective removal, but also by chemical changes in the soil. Livestock remove nutrients from certain locations, and add nutrients at other locations by faecal deposition (Miles, 1987). In locations with a higher nutrient status, more palatable grasses will take over from heather species (Section 2.4). This will attract additional animals, creating a greater local nutrient cycle (Welch, 1984a). This will not only have implications for species composition, but ultimately also for the soil and hydrology.

Hester and Baillie (1998) studied the grazing patterns of sheep on 1 ha plots with grass and heather patches on moorland in Scotland. It was shown that the greatest heather consumption by sheep coincides with its proximity to grass. Heather utilisation decreases rapidly with the distance from grass. The number of paths in grass patches, radiating out to surrounding areas, increased with the size of the grass patch. Seventy percent of all paths were generally grass covered, and the remaining thirty percent were either bare or moss covered, although this ratio differed considerably with patch size. The larger the grass patch, the more intensively the path is used and the higher the amount of moss-covered or bare paths, which could have important consequences for soil compaction, infiltration rates and eventually, overland flow (Hester and Baillie, 1998).

Vegetation utilisation by livestock varies through the year. In several studies conducted in Scotland (Welch, 1984a; Welch, 1984b; Armstrong and Milne, 1995), the relation between vegetation, season and livestock was established. In May, *Agrostis* and *Festuca* are utilised most. In mid July, species like *Molinia* and *Trichophorum* are preferred. In August and September, the utilisation of heather (*Erica tetralix*, *Erica cinerea* and *Calluna vulgaris*) and especially bilberry (*Vaccinium myrtillus*) increases, indicating that, when the grasses die back, bilberry is more palatable than heather species. Between October and

December, heather utilisation rises even further, while grass utilisation of *Trichophorum* fall. In winter, heather species are mostly preferred, but *Juncus squarrosus* and *Nardus* become increasingly popular as well (Welch, 1984a). In February, the intake of grasses increases again as new, palatable shoots are developed. As a consequence, the intake of heather decreases. In April, for a short period, *Festuca* and *Agrostis* are the most preferred (Armstrong and Milne, 1995).

This implies that, due to the increased heather intake in winter, a relatively small grazing area is under higher pressure. Additionally, during this period, soils are much wetter than in the summer period, increasing the risk of soil remoulding and compaction in heather stands, especially when the heather cover is not dominant and does not provide enough protection to the soil.

Also, livestock shows a daily grazing cycle. Sheep tend to spend morning and evening time roaming and grazing. During mid-day, they tend to spend their time in the same place close together (Clarke *et al.*, 1995). This is an important observation, as the stocking densities in these areas are very high in comparison to the roaming areas. There are some indications that grazing sheep are shifting from grass to heather at night-time, but timing and vegetation species are not known (Clarke *et al.*, 1995).

Although the behaviour as explained above gives a good example of livestock movements, it is rather generalised and cannot directly be applied to the Dartmoor area. An estimate of grazing pressures therefore needs to be carried out, before relationships can be established between grazing pressures, vegetation types and soil properties.

2.7.2 Grazing densities and impacts on vegetation composition

Intensive grazing can eliminate heather from moorlands (English Nature and Dartmoor National Park Authority, 1997). Thompson *et al.* (1995b) showed that in 1977, the moorland rough grazing area with more than 2 sheep ha^{-1} was 29%, while only ten years later in 1987, this area had increased to 71% in England and Wales. Bardgett *et al.* (1995) also related the condition of heather moorland in England and Wales to grazing pressure and showed that most heather species occurred in areas with less than 2 sheep ha^{-1} .

Under heavy grazing by sheep, heather species will be replaced by *Festuca ovina*, *Agrostis* spp., *Nardus stricta*, *Molinia caerulea*, *Juncus squarrosus* or *Eriphorum vaginatum,* depending on soil type and drainage. When cattle are involved the risk of heather decline is even greater because of the extra damage of trampling to the heather species (Welch, 1984a; Lance, 1987). However, when properly monitored, both sheep and cattle grazing can be an effective way of managing heather stands (Gimingham, 1995). On blanket bog, the number of grazing animals should be lower than on heather moorland, but grazing should not be excluded altogether, as it can act as a means of reducing stocking levels in other areas (Mowforth and Sydes, 1989).

Unfortunately, exact figures on maximum grazing pressures before heather decline occurs are scarce and cover quite a broad range of stocking densities. Evans and Felton (1987) for example, reported average sheep stocking rates from 0.44 ha^{-1} in the Welsh borders to 3.62 ha^{-1} in North-West Scotland. In North-East Scotland, average sheep densities were shown to be 2.7 ha^{-1} (Lance, 1987; Welch, 1984b). Maximum stocking rates of 2.0 ha^{-1} suggested by Mowforth and Sydes (1989) on heather moor and 0.37 ha^{-1} on blanket bog indicate that these maximum grazing pressures are regularly exceeded. Evans and Felton (1987) even suggested that stocking densities should be even lower at 0.5 and 0.1 ha^{-1}, respectively to allow heather to regenerate. The Royal Society for Nature Conservation (1996) suggested 1.6 and 0.5 ha^{-1}, respectively. Lance (1987) introduced a threshold based on vegetation degeneration between light and heavy sheep grazing at 0.45 ha^{-1}. These rates do not take into account effects on the soil, however.

MAFF (1994) studied maximum grazing levels for British moorlands as preparation for the moorland ESA. However, this section shows that in literature, the suggested maximum stocking densities for moorlands are highly variable. Therefore, there is a need for establishment of maximum densities for individual moorlands (Mowforth and Sydes, 1989).

2.7.3 Grazing impacts on soil physical properties

Grazing animals not only affect the vegetation, but can also have impacts on the soil, both chemically (Miles, 1987; Marrs *et al.*, 1989) and physically (Scholefield and Hall, 1986; Evans, 1996). The extensive removal of protective plant cover and trampling can cause soil damage. Different studies have shown conflicting results. Mwendera and Saleem (1997) indicated that trampling damage increases with increasing soil moisture, and Scholefield and Hall (1986) showed that the influence was dependent on both soil moisture and number of “treads”. Many soil properties are affected by trampling. Bulk density increases due to compaction (Ferrero, 1991; Greenwood *et al.*, 1998), soil organic matter of the topsoil decreases (Ferrero, 1991), aggregate stability decreases, and water infiltration decreases (Gifford and Hawkins, 1978; Taboada and Lavado, 1988; Evans, 1996).

Two processes can occur as a response to trampling; compaction and remoulding (Scholefield and Hall; 1986, Proffitt *et al.*, 1995). Compaction of the topsoil by hooves is most important at lower water contents, increasing the bulk density and thus decreasing the total porosity (Warren *et al.*, 1986). In near saturated conditions, the force of animal trampling causes weakening of soil structure by the disturbance of bonds between the particles, known as remoulding (Mullins and Fraser, 1980). Scholefield and Hall (1986) however, showed that for a sandy loam and a clay loam, the remoulding was higher than compaction for any soil moisture content.

Proffitt *et al.* (1995) showed, that bulk density, soil strength and infiltration in a well-managed pasture have a similar pattern to an ungrazed pasture, whereas a continuously grazed pasture deteriorated during wet spells. Sheep were removed from the well-managed pasture when the soil water content became close to the plastic limit. On the grazed plots, bulk density was much higher, porosity lower and therefore infiltration capacity lower. The rate of increase of soil strength by decreasing soil moisture was lower in the controlled and ungrazed plots than in the continuously grazed plots.

All studies highlighted in this section were focused on areas with high grazing intensities. Results of the research is difficult to relate to Dartmoor however, as not only grazing densities are different, but soils have a much higher organic matter content, making the soil much more susceptible for trampling.

2.7.4 Suggested grazing impacts on hillslope and catchment hydrology

As described in Section 2.7.2, animals prefer certain grazing areas to others. This has implications for the spatial distribution of trampling and its effect on hydrology at the hillslope and catchment scale. An increase in runoff and a decrease in storage induced by overgrazing has been reported by Evans (1996). In a period of thirteen years, in an area of the Dales in which sheep numbers increased by 40 %, four major floods were recorded, while summer flows were unusually low. During the same period, discharge volumes increased by 25 % (Evans, 1996; Sansom, 1996). This could be an indication of increased storm runoff, caused by reduced water storage. Orr (1997, in Sansom, 1999) also found a trend of increasing winter peak flows with decreasing summer low flows. Using records since 1900, she showed that the total annual rainfall did not show an increasing trend, but sheep numbers in the River Lune catchment in Lancashire have been on the increase since the beginning of records in 1860.

The nature of low summer flows is not known, but in a study on the uplands of Britain by Calder (1986) it was shown, that although evaporation rates from heather species are higher than from grass, grass transpires up to four times as much as heather. This may also account for the decreased low flows in summer.

These reports all indicate an influence of overstocking on the hydrological environment. However, more research needs to be done to link grazing pressures to hillslope and catchment hydrology.

2.8 Burning management

Burning of heather is common practice on heather moorlands in Britain (Gardner *et al.*, 1993; Mallik and FitzPatrick, 1996). Fire has a major impact on the ecology and may therefore be regarded as an important ecological factor (Gimingham, 1972). During a burn, a large amount of biomass is lost, and the succession to a new equilibrium will initiate. Separated from the direct impact of the heating of the topsoil, this change in vegetation and biomass will inevitably lead to a change in the soil, with consequences for the hydrology of the area.

Objective 2.3 (Chapter 1) emphasises the effects of burning management on soil properties. There is a need to examine the effects of altered soil properties and vegetation due to burning on plot and hillslope scale in order to estimate the impact of burning management on soil hydrology. The section is therefore structured as follows:

- Section 2.8.1 explains the background of burning as a management tool in moorland areas and the requirements of a properly carried out burn;
- In Section 2.8.2, conditions in the canopy and at the soil surface during a burn will be outlined;
- The impacts of burning on soil properties and soil hydrology will be described in Section 2.8.3.

2.8.1 Burning requirements

The main aims of burning in moorland management are (Gimingham, 1975):

- To prevent woodland re-colonising heathland;
- To avoid heather reaching the mature state of their growth cycle, in which most of the plant material becomes woody;
- To create evenly aged uniform patches with a high productivity of edible new shoots.

All three objectives are to stimulate herbage production to increase sheep production. Properly managed fire normally only burns the vegetation, leaving the remains of the thicker stems of the heather. Although ground covering plants and mosses are usually burned, the soil covering litter and humus layer is left untouched (Gimingham, 1975), indicating a limited direct effect of the burn to the soil. If not correctly controlled, fire may burn into the humus and sometimes even into highly organic soil or peat down to the mineral soil if the fire gets extremely hot (Gimingham, 1975). Some fires have been known to continue for days or even weeks (Johns, 1998). These exceptionally hot fires are more likely to happen in summer, when the vegetation and soil is much drier than in winter (Radley, 1965; Imeson, 1971; Wein, 1983; Maltby *et al.*, 1990).

The law only allows burning during a certain period of the year. In England, this period is between 1 November and 15 April (Gimingham, 1975; MAFF, 1992). The Dartmoor National Park Authority however recommends commoners to finish the burning season before 31 March because of the bird-nesting season (DNPA, 1997; Goodfellow, pers. comm., 1998). In terms of guidelines to burning, the Dartmoor National Park Authority (1997) states:

> "No moorland may be burned where heather is present for more than an area of 900 square metres at intervals less than 12 years, nor where the distance between burns in any one year is less then 150 metres. No person shall burn moorland where dead grass is present on any common land unit over an area exceeding 20 hectares or 25 % of that area of that common land unit whichever shall be the less and such burning shall take place at intervals no less than 3 years."

Burning grasses, mainly *Molinia*, is also widespread in moorland management on Dartmoor. Accumulated inedible grasses are removed, so new nutritious grass shoots are encouraged. Species like *Molinia*, *Agrostis* spp., *Vaccinium myrtillus*, *Nardus stricta* and *Festuca* are relatively resistant to fire. Burning is very effective in managing rough grasslands, especially when ungrazed or undergrazed and where there is a large accumulation of dead material (Duffey *et al.*, 1974).

The optimal burning cycle of heather is 10-15 years (Gimingham, 1975). Unfortunately, this is rarely achieved and burning is irregular in many places. Some areas are burned every two-three years, whereas other areas rarely get burned at all. In some areas, old stands of heather that have not been burned for a long time are not grazed, increasing the pressure on younger stands, especially with the current grazing intensities. Fires in old stands are very likely to create fires that are too hot for regeneration of the heather (Hester and Sydes, 1998). Both elsewhere and on Dartmoor, there are indications that burning has been on the increase and much of the upland heathland is lost due to frequent and extensive burning (Tallis, 1987; Wolton *et al.,* 1994; EN/DNPA, 1997).

2.8.2 The effects of fire on the soil

For many years, concerns have been raised over the effect of fire on moors (Radley, 1965, Imeson, 1971, Johns, 1998). Soil organic matter content decreases at high temperature levels (Forgeard and Frenot, 1996). Burning may cause impacts on all soil properties that are dependent on organic matter, like aggregate stability, structure, pore space (DeBano, 1991), causing reduced infiltration rates. Post-fire soil degradation may include surface layer water repellency, causing greater overland flow and even erosion (Imeson, 1971; Kinako and Gimingham, 1980; Imeson *et al.*, 1992) mainly due to the soil surface structure, instead of the vegetation removal (Emmerich and Cox, 1994). A distinction has to be made between controlled rotational burning by hill farmers and the much more devastating wildfires (Imeson, 1971).

2.8.3 Conditions during a burn

To estimate burning impacts on soil properties and hydrology, a basic understanding of burning conditions in the plant canopy and at the soil surface during a fire needs to be established. As higher temperatures and longer burns are very likely to have a greater effect, it is important to know what factors are influencing burning temperatures and burning time span.

The first experiments in establishing fire temperatures in heather stands involved temperature sensitive paints, so called 'thermocolours'. They were painted on small strips of mica and left at different positions within the vegetation and soil, just before the area was burned. Whittaker (1961) found that maximum temperatures are typically 500 to 840 °C at 20 cm above the soil surface, but at ground level, lower temperatures of between 300 and 500 °C were reached. At 1 cm depth below the peat surface, however, temperatures only rose by 30 °C, demonstrating the insulating capacity of the litter and humus layer (Gimingham, 1975). Other temperatures reported at ground level on heathland soils are between 50 and 430 °C (Forgeard and Frenot, 1996), up to 940 °C with an average of 670 °C over 35 fires (Kenworthy, 1963), and 755 °C (Mallik *et al.,* 1984).

However, in these studies the temperature in the soil was not measured. Also, the values measured only indicate the maximum temperatures reached, and do not give an indication about the change in temperature through time. Using thermocouples, both the temperature and time during the burn can be recorded. Findings by other researchers (Kenworthy, 1963; Kayll, 1966) found similar temperatures to Whittaker (1961), and showed that maxima only lasted for about 30 to 60 seconds. The period from the beginning of the increase until the return to normal seldom exceeds 2½ minutes (Gimingham, 1975), showing the short time span of a burn.

Forgeard and Frenott (1996) also monitored the shallow temperature effect during a laboratory experiment under a Britanny heathland soil. During soil surface heating to up to 300 °C, the temperature at 1 cm depth only reached about 70 °C after ten minutes of continuous heating. In a laboratory experiment using a column of sand, Aston and Gill

(1976) also showed that after 5 minutes of heating at 420 °C, temperatures at 3 cm depth barely increased.

Forgeard and Frenott (1996) also made a distinction between light and intense fires, with light fires with a soil surface temperature of up to 150 °C and an increase of temperature of less than 15 minutes. Fierce fires reach temperatures up to 300 °C for a longer time (30 mins), which, as has been suggested by Gimingham (1975) is relatively long for heather burns.

The temperatures and the time span depend on weather conditions, especially wind speed. (Soil) temperature is also determined by rate of passage, soil moisture content, vegetation type and fuel load both from the vegetation and the litter layer (Gimingham, 1975). The experiments with thermocouples revealed a clear relationship between temperature and age of stand. The older the stand, the greater amount of biomass or fuel load and therefore the more intense the fire (Gimingham, 1975). This intensity combined with the time span is a key factor in the impact of fire on soil properties.

2.8.4 The effects of burning on soil properties

Heating of soil has effects at different stages or thresholds (Giovannini, 1994). In the range up to 170 °C, desiccation of the soil is the main process. From 170 to 220 °C, the gel forms are being dehydrated, and then the combustion of organic matter takes place (Giovannini, 1994; Forgeard and Frenot, 1996) between 220 and 460 °C (Giovannini, 1994). Above this temperature, clay particles lose its OH groups (550 to 700 °C, Giovannini, 1994), changing the texture of the soil to larger particle sizes (Burgy and Scott, 1952; Giovannini, 1994) and up to 900 °C, carbonates are decomposed (Giovannini, 1994). Giovannini also found that because of the removal of organic matter, which contributes to the soil structure, the structure breaks down, changing the soil porosity (Giovannini and Lucchesi, 1997). It is not clear if these results only apply to mineral soils, or if peat or soils with a high organic matter content behave in the same manner. However, it has been shown that under heather burns, soil temperatures are relatively low, suggesting that the above effects are limited

Earlier research on effects of burning on water infiltration has shown conflicting results: Mallik *et al.* (1984) report decreased water infiltration on heather moorland, while Kinako (1975, in: Mallik, 1984) stated that infiltration was increased by 50 % on burned heathland soils. Burgy and Scott (1952) report no difference between burned and unburned areas in forested areas in terms of infiltration. As infiltration rates are important factors in determining the different pathways, this needs to be taken into account in this study.

In a study on the erodibility of soil after burning on the Hill of Fare and Kerloch moors (Scotland), a decline of the soil surface was shown of between 0.27 and 0.55 cm, mainly in the first eight months after burning (Kinako and Gimingham, 1980). This study did not study the processes behind erosion initiation, however.

In their study on the impacts of heather burning on soil water characteristics, on the Muir of Dinnet in Scotland, Mallik *et al.* (1984), showed that the infiltration capacity decreased but the soil retained more water after a burn, compared to an unburned soil. This effect was most profound in the top 2 cm of the soil, but was measurable down to 10 cm. In cores taken from 0-2 cm, the soil retained more water over the whole pF-curve. However, lower in the profile, in cores taken from 2-6 and 6-10 cm depth, burned soils retained more water when lower than pF 1. Closer to saturation, unburned soils retained more water (Mallik *et al.*, 1984). Mallik *et al.* (1984) explained the decrease in infiltration by the blocking effect of pores by ash in the upper soil layer. Therefore, the amount of large pores decreases, whereas the relative proportion of smaller pores increases. So, the percolation capacity through the topsoil decreases, whereas the water retaining capacity of the soil increases (Mallik *et al.*, 1984).

Ternan and Neller (1999) however showed that under grasslands in the humid tropics lower amounts of water were held (at most suctions) in samples shortly after a wildfire than samples with a longer recovery time. They also found a positive correlation between the transmission-storage pores ratio with aggregate stability, whereas ash translocation did not seem to have an effect. This indicates that when aggregates collapse, the proportion of transmission pores in the soil declines (Ternan and Neller, 1999). The difference between the results of the above experiments might be attributed to the timing of the soil sampling *i.e.* after the fire but before the first rainfall or after rainfall. This may influence the washing of ash into the soil (Ternan, 1999, pers. comm.)

Hydrophobicity, the 'unwettability' of the soil is mostly due to the irreversible desiccation of the organic matter during high temperatures (Dekker, 1998; Ritsema, 1998). However, if the temperature becomes high enough for the organic matter to be burned, this phenomenon disappears (Giovannini and Lucchesi, 1983).

In a study on the temporal effects of a burn on soils, Giovannini *et al.* (1987) found that after three years the soil surface had regained its original properties, but in the subsurface translocated hydrophobic substances were still present.

In the same study as above by Mallik *et al.* (1984), infiltration turned out to be significantly lower after a burn even after an extensive period. This is probably still due to the blocking of pores by ash remains of the fire, but water repellency, for example, can cause this effect as well. This study does not give any information on soil moisture status at the time of sampling, or about the weather conditions period prior to the sampling. A relatively long spell of drought, for example, after the burn can be expected to increase the effect of the burn itself, as the soil is bare and dries out more quickly than covered soil.

As described above, burning is known to affect soil moisture, porosity, water retention, infiltration and organic matter contents. Although considerable research has been done on burning impact on soils, no investigations on scale effects and impacts on hillslope hydrology have been conducted. Therefore, spatial links to hillslope hydrology should be established to understand burning impacts on a wider scale. Effects of burning on important hydrological soil properties should be investigated, and the effect of removal of vegetation on hydrological processes must be estimated.

2.9 *Agricultural policies and the economy*

This section gives a brief outline of the economics of the upland and hill farming in Britain, in order to get an understanding of the current situation of farming on the moors.

Since the 1880s, upland farming has been in decline (Collins, 1978). The government recognised the parlous state of upland farms in the 1940s with the Hill Farming Act (1948). In spite of government subsidies however, the combination of economic pressures and environmental controls has reduced the number of farms considerably. In Wales, the total number of hill farms was reduced by 15% between 1966 and 1974, for example, whereas a reduction of 45% in the uplands of the whole country was recorded (Jones, 1978). Financial aid was becoming available for farms with economic problems, and farmers were actively encouraged to plough or re-seed rough grazing land and to increase their livestock (Jones, 1978; Evans and Felton, 1987). Therefore, despite the reduction in number of farms in the hills, sheep numbers increased dramatically as a result of the governmental policies. For example, the total number of sheep in the UK increased from 22 million in the 1940s to 44 million in 1993 (Sansom, 1999).

In the mid-seventies, it was realised that hill cattle and sheep headage payments were making up a substantial amount of the net incomes of hill farmers (Maxwell *et al.*, 1987). On average 20% of the total gross output and between 40 and 74% of their net income in 1974-76 of farmers consisted of financial government aid (Jones, 1978). It was shown, that farming was out of line with the economic situation of that time, with still too many small farms. The question was raised whether to move sheep farming out of the hills and to intensify farms in the lowlands (Jones, 1978; Maxwell *et al.*, 1987). However, little was done to change the situation.

At the present time, sheep farming in the uplands of Britain would not be economically viable without subsidies (Evans and Felton, 1987; Maxwell *et al.*, 1987; Sansom, 1999). Prices of sheep on the market have dropped dramatically in the mid 1990s. In terms of grants, farmers received up to £30 per sheep in 1998, composed of the Sheep Annual Premium (SAPS), covered by the EU and the Hill Livestock Compensatory Allowance (HLCA) (MAFF, 1993; MAFF, 1997), which totalled £655 million for British farmers. The HLCA does not encourage better management or productivity, but merely causes an increase in stocking rate (Anderson, 1989). However, changing the HLCA policies alone cannot be used to reduce stocking rates. EU grants are at least two-thirds of the total grants to farmers (Evans and Felton, 1987).

The outbreak of Foot and Mouth disease in early 2001 has also severely affected the sheep farming industry, with several cases in moorland areas, including Dartmoor. This outbreak, which also affected other countries within Europe, has contributed to a review of the agricultural policies at British and European level (Crowe, 2002, pers. comm.).

The grants for livestock have undoubtedly encouraged hill farmers to increase their livestock, whereas at the same time, it has been realised that overstocking on the moorlands is causing extensive damage to the environment (Sansom, 1999). It is also realised however, that limited grazing on heather moorlands is needed for a sustainable management of the heather vegetation community. Therefore, the Environmentally Sensitive Area (ESA) scheme was introduced in 1994. In this scheme, which applies to large areas on Dartmoor (Chapter 3), sheep farmers are actively encouraged by subsidies to reduce livestock numbers to appropriate levels, and to regulate the timing of grazing.

Chapter 3: The study area

3.1 Introduction

This chapter describes Dartmoor in general (Fig. 3.1) and the study area near Venford Reservoir in particular. First, the site selection of the study catchment is described. Then, principal characteristics of the geology, geomorphology, topography, climate, hydrology, soils, vegetation and land management are addressed for Dartmoor. Where data are available, a detailed description of the study area on Holne Moor is given.

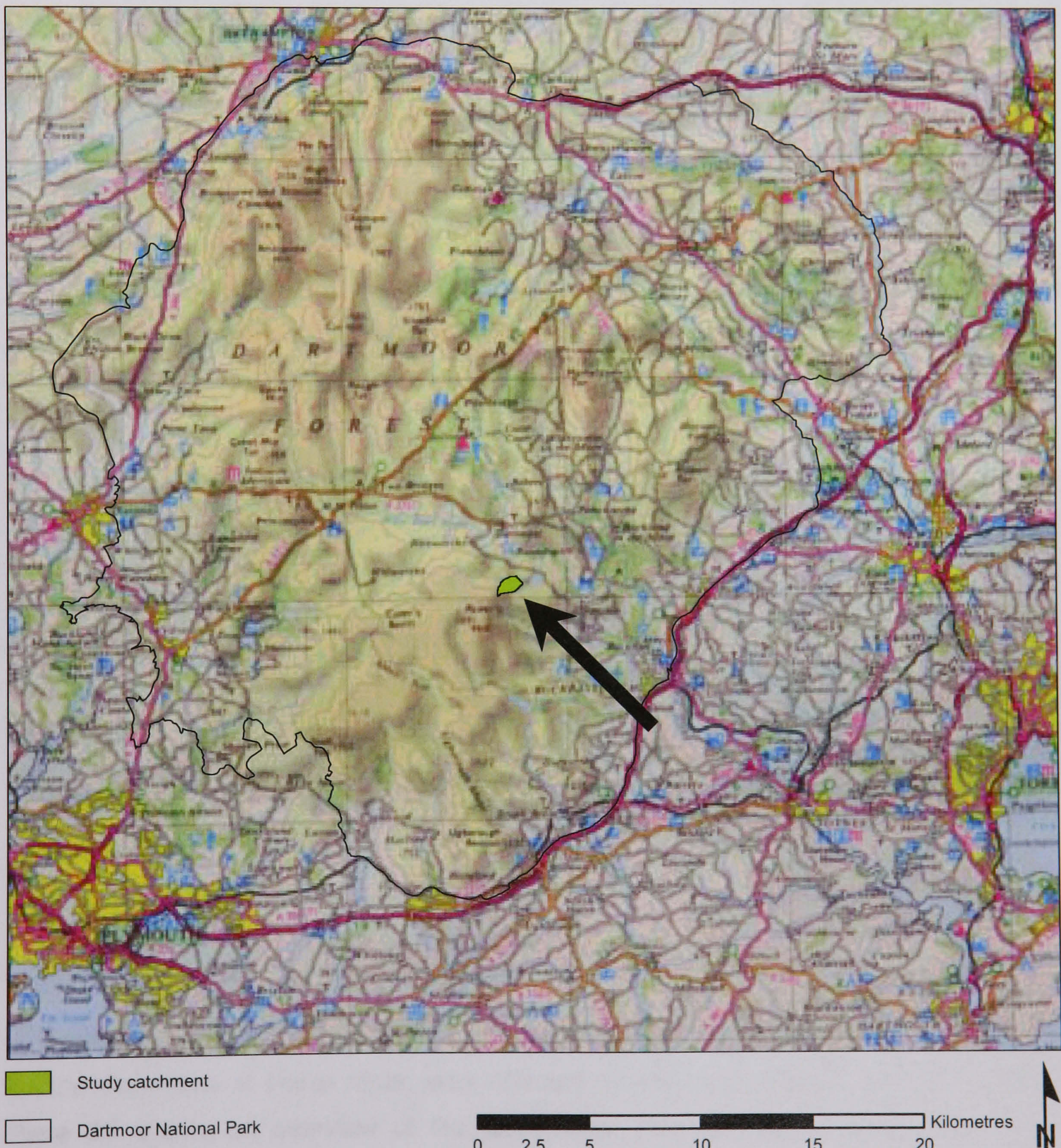


Figure 3.1: Map extract (original scale 1:250,000; © Ordnance Survey) of Dartmoor. The study area near Venford reservoir is indicated by the arrow.

3.2 Site selection

3.2.1 Selection criteria

A potential study site had to meet several criteria in order to fulfil the aims of the research:

i. A study site was required in an area representative for Common Land on Dartmoor. Such areas are outside enclosed farmland, typified by rough grazing moorland.

ii. On Dartmoor, the topography and soils of many catchments is altered due tin streaming or quarrying in the past. Disturbance needed to be minimal to be able to study the natural hydrological pathways.

iii. For studying the hydrology of the catchment, the boundary of the watershed needed to be clearly definable on the convex hillslopes.

iv. Vegetation should generally reflect the common occurrence of semi-natural species on Dartmoor. Different heather species (*Calluna vulgaris* and *Erica* dwarf shrubs), gorse (*Ulex* spp.) and different grasses (*Molinia caerulea*, *Festuca ovina*, *Agrostis capillaris*) should be present.

v. Typical Dartmoor soil associations had to be present, to enable comparison with other catchments with similar soils and soil catenas.

vi. For practical reasons, easy access was an advantage.

Plate 3.1: The study area.

3.2.2 The research site

A small headwater catchment (61 ha) of the Venford Brook (grid reference SX 675706), on the Commons of Holne Moor, was selected on the south-eastern side of Dartmoor. Plate 3.1 shows an overview of the study area. The catchment drains into Venford Reservoir (Fig. 3.2 and Plate 3.2), which is used as drinking water supply and is owned and managed by South West Water. The catchment is situated near a road, and a car park, about 1.5 km from the study area, facilitated easy access. During the building of the reservoir dam, boundary stones were erected, marking the water divide on the northern and western side of the watershed which enabled easy watershed delineation.

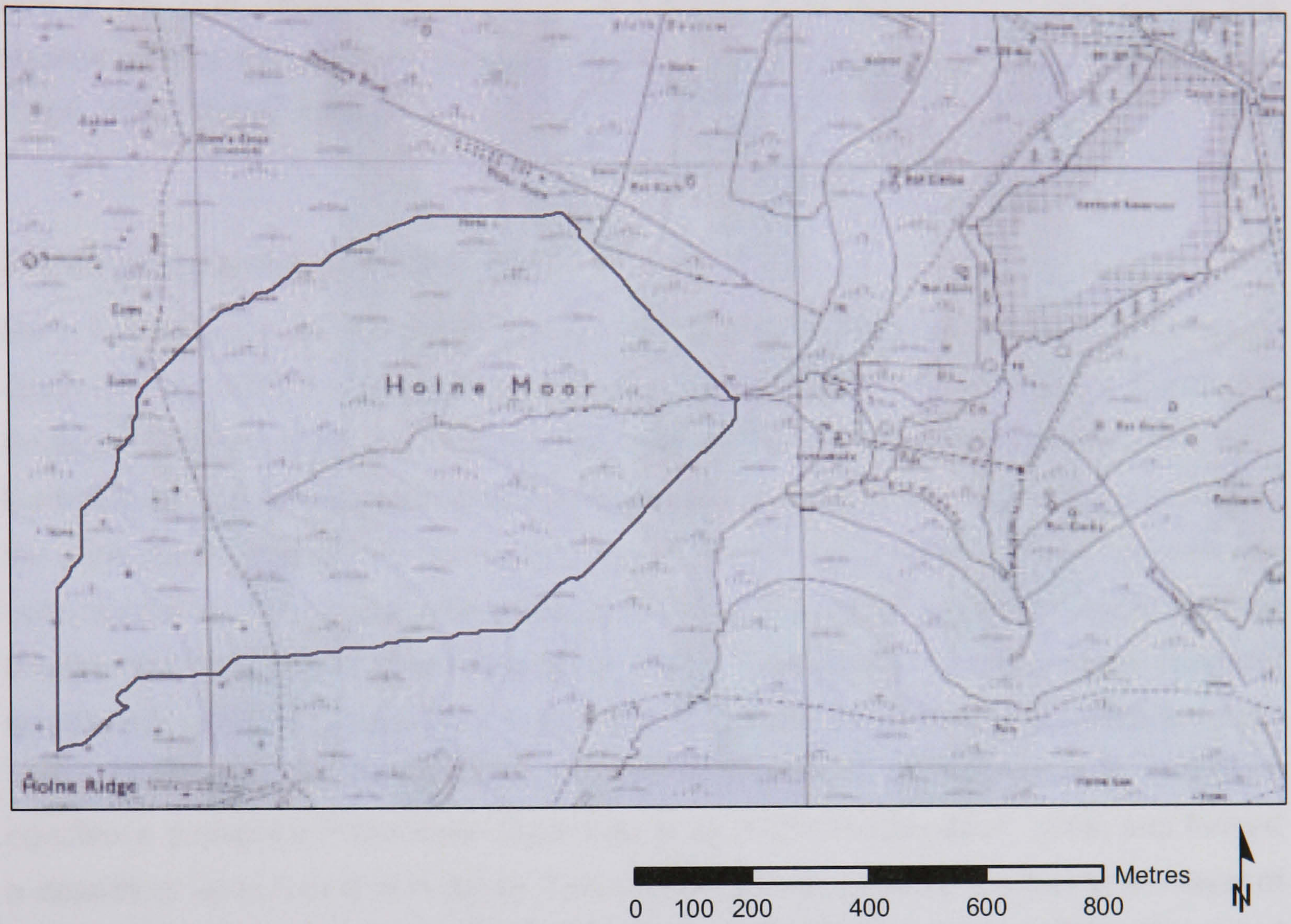


Figure 3.2: Map extract (original scale 1:10,000; © Ordnance Survey) of the research area on Holne Moor, west of Venford Reservoir.

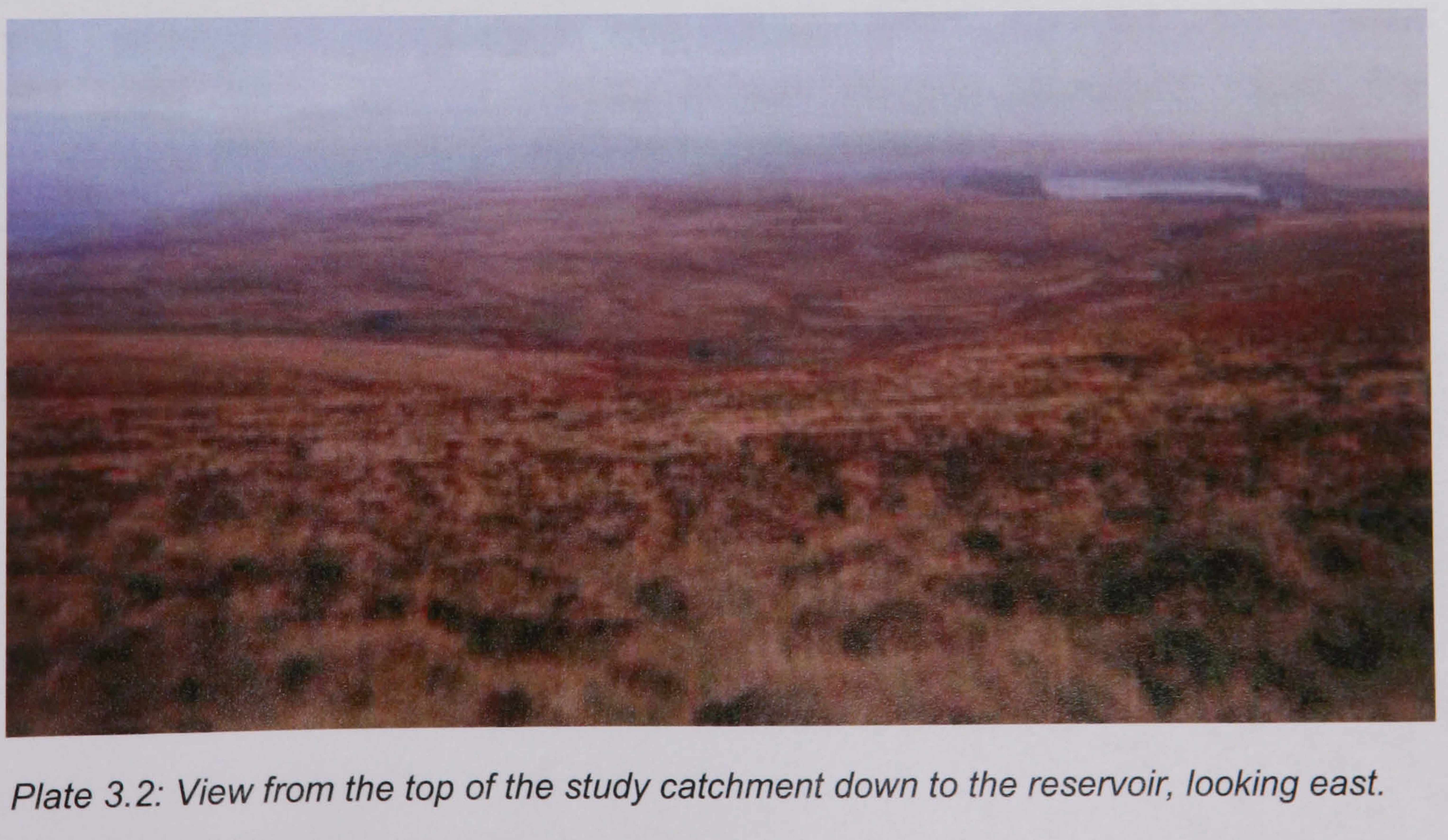


Plate 3.2: View from the top of the study catchment down to the reservoir, looking east.

The soils and topography in the study area have been affected in several ways in the past. The valley bottom has been disturbed by tin streaming between the 13th and 19th century, but not as extensively as in many other valleys on Dartmoor. On the northern side of the river, remains of medieval agricultural fields have been found. A leat was created across the southern hillslope, but is not actively carrying water (Fleming and Ralph, 1982; Butler, 1993).

3.3 Geology and geomorphology

Much of the geology of Dartmoor National Park consists of granites (Geological Survey of Great Britain, 1977). The hard resistant rock forms most of the uplands in Southwest England, including Dartmoor, Bodmin Moor and the Isles of Scilly (Findlay *et al.*, 1984).

Dartmoor has never been glaciated but Pleistocene periglacial environments have shaped the area. Tors, large granite outcrops on the top or sides of the hills have formed either in both tropical and periglacial environments (Linton, 1955) or by periglacial processes only (Palmer and Neilson, 1962; Williams *et al.*, 1986). They occur in locations where chemical weathering rates and erosion are higher than the profile weathering rate (Williams *et al.*, 1986). Weathered granite (growan) was relocated downhill by gelifluction in periglacial conditions during the Pleistocene (Edmonds *et al.*, 1975; Findlay *et al.*, 1984) and formed a deposit of up to 5 or 6 m in depth. This deposit, known as head, overlies a thin layer of in situ weathered granite saprolite (Cullingford, 1982; Findlay *et al.*, 1984). The head deposits are thickest on the lower parts of the slopes, but due to the high variability, this not statistically significant (Gerrard, 1989). The head generally consist of coarse materials with a larger proportion of gravel (> 2mm; Gerrard, 1989) and sand (0.5 – 2 mm; Green and Eden, 1973), probably resulting in high saturated conductivity values. The hydrological characterisation is described in Sections 3.5 and 3.6.

A layer of peat, between 50 cm up to 7 m in thickness, covers more than a third of the unenclosed moorland. The main extent of the peat is as blanket bog on the two plateaux, but can also be found in the valley mires (Findlay *et al.*, 1984).

The altitude of the Dartmoor National Park ranges from 22 to 621 m (Fig. 3.3). Slopes are generally gentle, but can be steep in places. The general form of the hills consists of smoothly rounded convex gently sloping hills with wide basins (Findlay *et al.*, 1984). The joints of the granite determine the topography of Dartmoor locally, which can be seen especially from river courses (Brunsden and Gerrard, 1977).

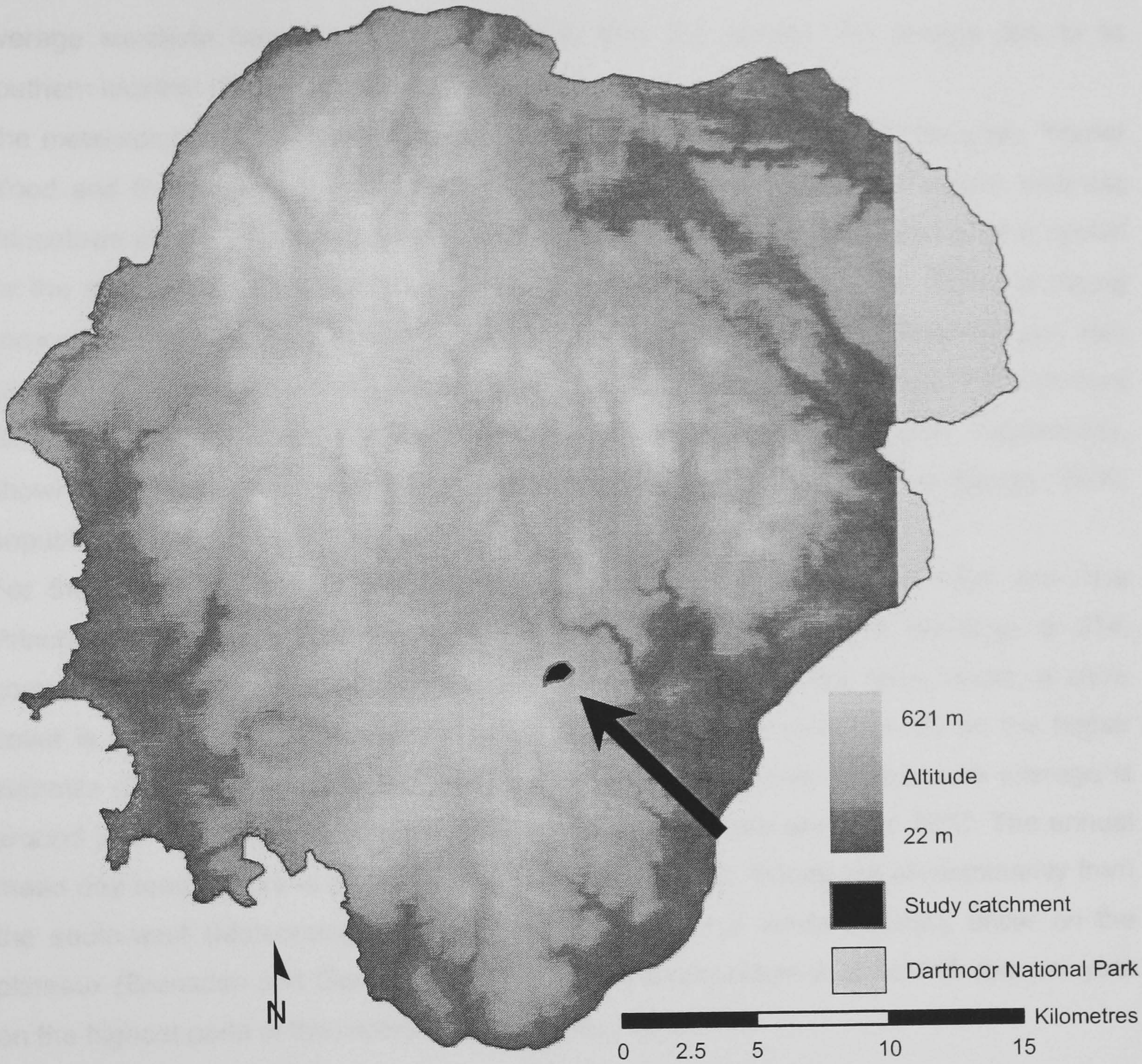


Figure 3.3: Digital Elevation Model of Dartmoor (© Ordnance Survey). The grey area on the right indicates missing data.

In geological history, rivers eroded the granite leaving flood plains and wide valleys. In several uplift stages, terraces were formed. Initially, rivers flowed east. During the mid-Tertiary, the Dartmoor massif was tilted southwards by Alpine movements, and rivers started to run south. The main drainage patterns is currently still in this direction, with only two rivers flowing north and eight main rivers flowing south, including the Dart and the Tavy (Brunsden and Gerrard, 1977).

3.4 Climate

The general climate of Dartmoor is one of relatively mild winters and cool summers with relatively high rainfall. The microclimate varies mostly with aspect, altitude and distance to the sea (Findlay *et al.*, 1984). Although the annual precipitation is relatively high, the average sunshine hours per year are higher than the annual UK average due to its southern location (Brunsden and Gerrard, 1977).

The meteorological office has three weather stations on Dartmoor: Okehampton, Yarner Wood and Princetown. Yarner Wood is situated at the lee-side of the moors, whereas Princetown (414 m) is the highest and most exposed location. The average annual rainfall for the stations are 1300 and 2100 mm per year, respectively. Rainfall shows a strong correlation with altitude (Meteorological Office, 1983). South West Water has two rain gauges situated close to the study area. The long-term annual rainfall near Venford Reservoir (290 m) and on Ryder's Hill (500 m) is 2022 and 2452 mm, respectively, showing the increase of precipitation with increasing altitude (Environment Agency, 2000, unpublished data).

For the period 1941-1970, the long-term average annual rainfall was 1924 mm near Princetown (Meteorological Office, 1983). The average number of rain-days is 214, compared to 160 for the surrounding lowlands of Devon. On the open moors, a snow cover is present for 15-20 days on average per year and more than 30 on the higher summits (Brunsden and Gerrard, 1977). The winter mean daily temperature average is around 3 to 4°C, whereas summer mean daily temperatures are 14 to 16°C. The annual mean day temperature is 8° (Meteorological Office, 1983). Winds are predominantly from the south-west (Meteorological Office, 1983). Gale force winds regularly occur on the plateaux (Brunsden and Gerrard, 1977). Potential transpiration is about 400 mm per year on the highest parts of the moors (Findlay *et al.*, 1984).

3.5 Hydrology

Drainage patterns on Dartmoor are mostly radial on the large convex summits. The total drainage area per unit length of river is relatively high in comparison to other catchments in Britain (Brunsden and Gerrard, 1977), probably due to a combination of the relatively high permeability of the Dartmoor granite and the large water holding capacity of the peat and weathered rock. This water holding capacity results into a steady discharge of groundwater into the streams as baseflow (Brunsden and Gerrard, 1977): the blanket peats are wet throughout the year and supply a steady flow of water to the streams (Findlay *et al.*, 1984). Findlay *et al.* (1984) state that during winter rainfall, when the soils are saturated, overland flow causes runoff on several soil types and consequently causes a quick river response after rainfall. The Narrator Brook, in the southwest of Dartmoor, also shows the flashy nature of a typical Dartmoor stream (Williams *et al.* 1984; Solman, 2000, unpublished data). It is also known that the Dart and especially the Tavy show a very quick response in discharge levels after rainfall (Sitch, 2000, pers. comm.).

Williams *et al.* (1984) distinguished four main subsurface flow pathways on Dartmoor hillslopes: (i) flow above an ironpan, (ii) flow above a fragipan, (iii) saturation upward from a fragipan and (iv) saturation within a fragipan. This fragipan is an indurated horizon, which is associated with periglacial activity and occurs locally at a depth between 60 and 90 cm (Williams *et al.*, 1984). Overland flow can be regarded as a fifth pathway.

These five pathways can be combined into one overall model at the hillslope scale. On the top of the slope on the moors, the soil above the ironpan of the ironpan stagnopodzols is saturated throughout most of the year. Rainfall induces upward saturation above this ironpan, causing overland flow. This flow is thought to contribute to tributaries and generates a quick response in watercourses, typical of Dartmoor streams.

On the slope, on the brown podzolic soils, two pathways occur: at the top of the slope, the highly indurated fragipan limits vertical percolation of water through the soil, causing lateral flow through the humose mineral topsoil (Ah), the sesquioxide rich Bs horizon and the granite regolith (B/C). Further down the slope, both rainfall and percolating water from upslope contributing areas cause saturation upwards in the soil above the fragipan. Flow through an unindurated fragipan also occurs depending on water head and position on the slope. Infiltration excess overland flow occurs commonly across the whole hillslope.

Other factors that are characteristic of the hillslope hydrology of Dartmoor are networks of springs and seepages at the base of the slope in concave depressions, and fissures in the underlying granite and vertical variation in permeability in the regolith (Williams *et al.*, 1984). The description of Williams *et al.* (1984) shows the importance of the spatial variability of the topsoil to soil water transport at the hillslope scale.

3.6 Soils

Upland peats cover large areas of Dartmoor. They mainly occur as blanket bogs (raw oligomorphous peat), but also occur in the basins (basin peat; Findlay *et al.*, 1984). In general, Dartmoor can be subdivided into several large units. The north-west and south of the moor consist of two relatively high altitude plateaux with extensive blanket bog areas, whereas in the north-east, where the landscape is lower, the soils are more podzolic and better drained (Findlay *et al.*, 1984).

Soils on Dartmoor are mostly classified as the Crowdy 2, Princetown, Hexworthy, Moor Gate, Laployd and Moretonhampstead soil associations as described by the soil classification of the Soil Survey of England and Wales (1983a and 1983b). Each association is a combination of soil series, single soil unit classifications (Soil Survey of England and Wales, 1983a; Findlay *et al.*, 1984). In the following section, soils are described according to their occurrence in the soil catenas typical of a Dartmoor hillslope, from top to bottom (Fig. 3.4). In the second section, the occurrence and distribution of the soils of the Holne Moor area are described.

3.6.1 The typical Dartmoor soil catena

Crowdy 2 association

Blanket peat covers the upper parts of the hills, with thick raw acid peat soils. Well-humidified peats are most extensive, but are accompanied by a more fibrous peat. The latter mostly occupy perennially waterlogged hillside flushes and basins where peat is still growing. The soils are often at near saturation due to the high annual rainfall of over 2000 mm per year at this altitude. The blanket bogs have been described to be important runoff regulators (Soil Survey of England and Wales, 1983a; Findlay *et al.*, 1984).

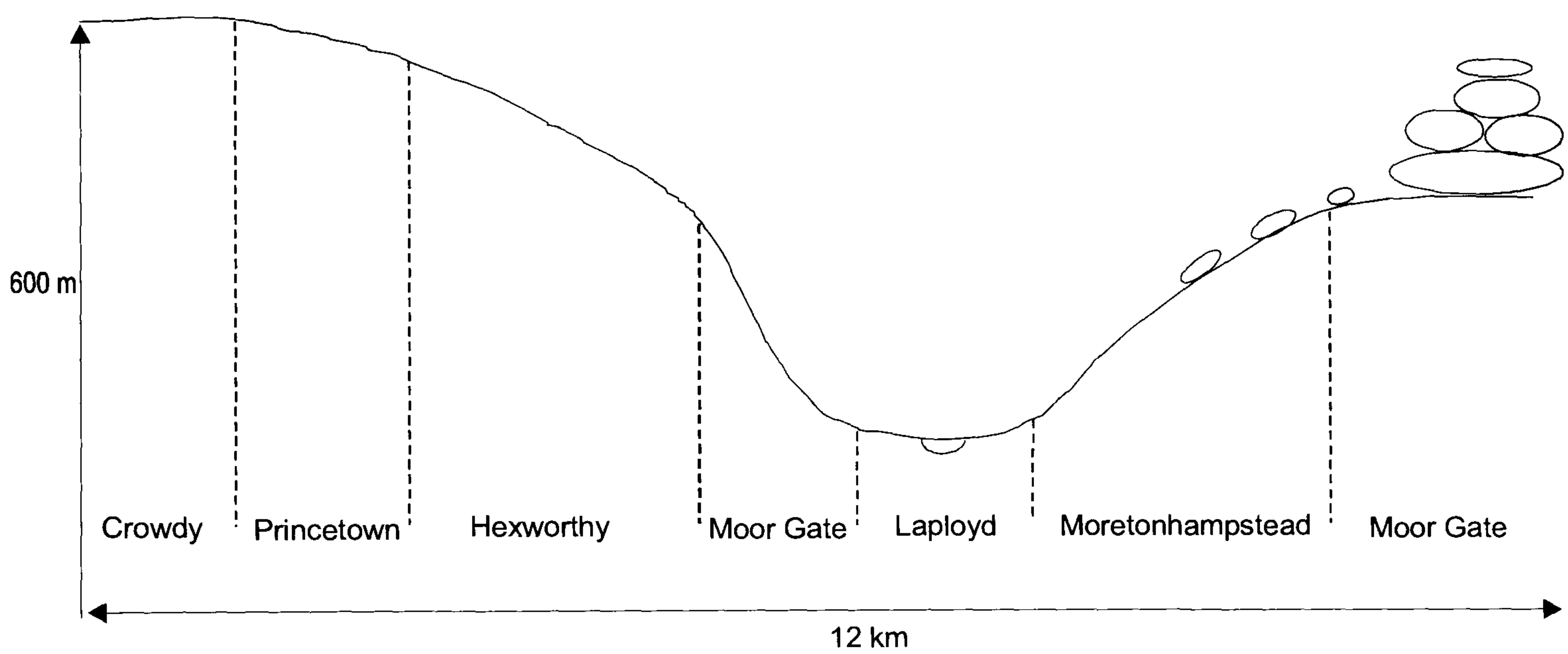


Figure 3.4: Schematic diagram of Dartmoor soil associations. After Findlay et al., 1984.

Princetown association

The Princetown association is situated on the higher parts of the moors. It covers gentle or moderate slopes under *Molinia* grassland and mostly lies above 300 m. It surrounds the blanket bogs of the Crowdy 2 association (Fig. 3.4). The majority of the soils are coarse loamy cambic stagnohumic gleys of the Princetown series (Harrod *et al.*, 1976) which developed in growan, often compacted at shallow depth. A grey, often slowly permeable sandy loam horizon underlies a thin peaty topsoil. Locally, this topsoil is more than 40 cm in depth. The soils are permanently wet. In high rainfall areas, they are waterlogged throughout the year, even if the subsoil is relatively permeable in places. Winter rains cause overland flow on these soils. In summer, they store rainwater, regulating river discharge to the Dartmoor headwaters (Findlay *et al.*, 1984).

Hexworthy association

The Hexworthy association can be found on gently or moderately sloping land, especially on the eastern margin of the peat-covered northern plateau. The soils also occur on the southern plateau, although are less extensive in area. The association mainly consists of podzolic soils, developed in the coarse loamy material of the granitic head. More than 50 % of the soils are ironpan stagnopodzols, but cambic stagnohumic gleysoils and humus ironpan stagnopodzols are also widespread. However, there is great variety in proportions from place to place. The short distance variation is characteristic for this association. The presence of the ironpan varies and different profiles grade into each other. The soils are often waterlogged in the topsoil due to the presence of the ironpan, whereas the subsoil is more permeable. Winter rain often causes overland flow on these soils. The soils are only suitable for seasonal grazing (Findlay *et al.*, 1984).

Moor Gate association

The Moor Gate association can be found on the unenclosed moorland margins, mostly on the steeper slopes. They are mostly podzolic, in gravel parent material with local additions of silty drift. More than half of the association is taken up by coarse loamy humic brown podzolic soils, with a dark humose topsoil over a finely structured permeable brown or brightly coloured subsoil, consisting of gritty sandy (silt) loam. Brown podzolic soils and ironpan stagnopodzols take up the rest. As soil type boundaries are gradual, they form a complex association. The soils are much more permeable than the ones described previously and generally do not induce overland flow during winter, except on the steepest slopes (Findlay *et al.*, 1984).

Laployd association

The Laployd association can mostly be found in the valley bottoms, together with some Crowdy 2 areas. It consists of groundwater gley soils in stony loamy drift. The main soils are humic gley soils with a humose or peaty topsoil over a mottled sandy (silt) loam subsoil, which gradually changes into a very stony horizon at shallow depth. The soils are relatively permeable, but because of their position are often waterlogged. In winter especially, they receive large amounts of water from the higher areas, causing extensive overland flow (Findlay *et al.*, 1984).

Moretonhampstead association

The Moretonhampstead soil association also covers the higher ground in areas where tors, boulders and clitter are present. The association mainly consists of coarse loamy typical brown podzolic soils. They are well drained and can absorb winter rain except for soils located on steeper slopes (Findlay *et al.*, 1984).

3.6.2 Soils in the study area

Hogan (1988) mapped the soil of the area west of Venford Reservoir (1:25,000) for a moorland vegetation project carried out by Dartmoor National Park. Most soils were of the Hexworthy and Laployd-associations, whereas a small area on the west bank of the reservoir consisted of the Moor Gate association (Fig. 3.5). Within the catchment, the Laployd association, with permeable gritty loams with black humose or peaty topsoils occupied most of the southern slopes. These soils are relatively wet due to lateral seepage, probably originating from the higher located blanket bogs. Humic gley soils often have peaty topsoils.

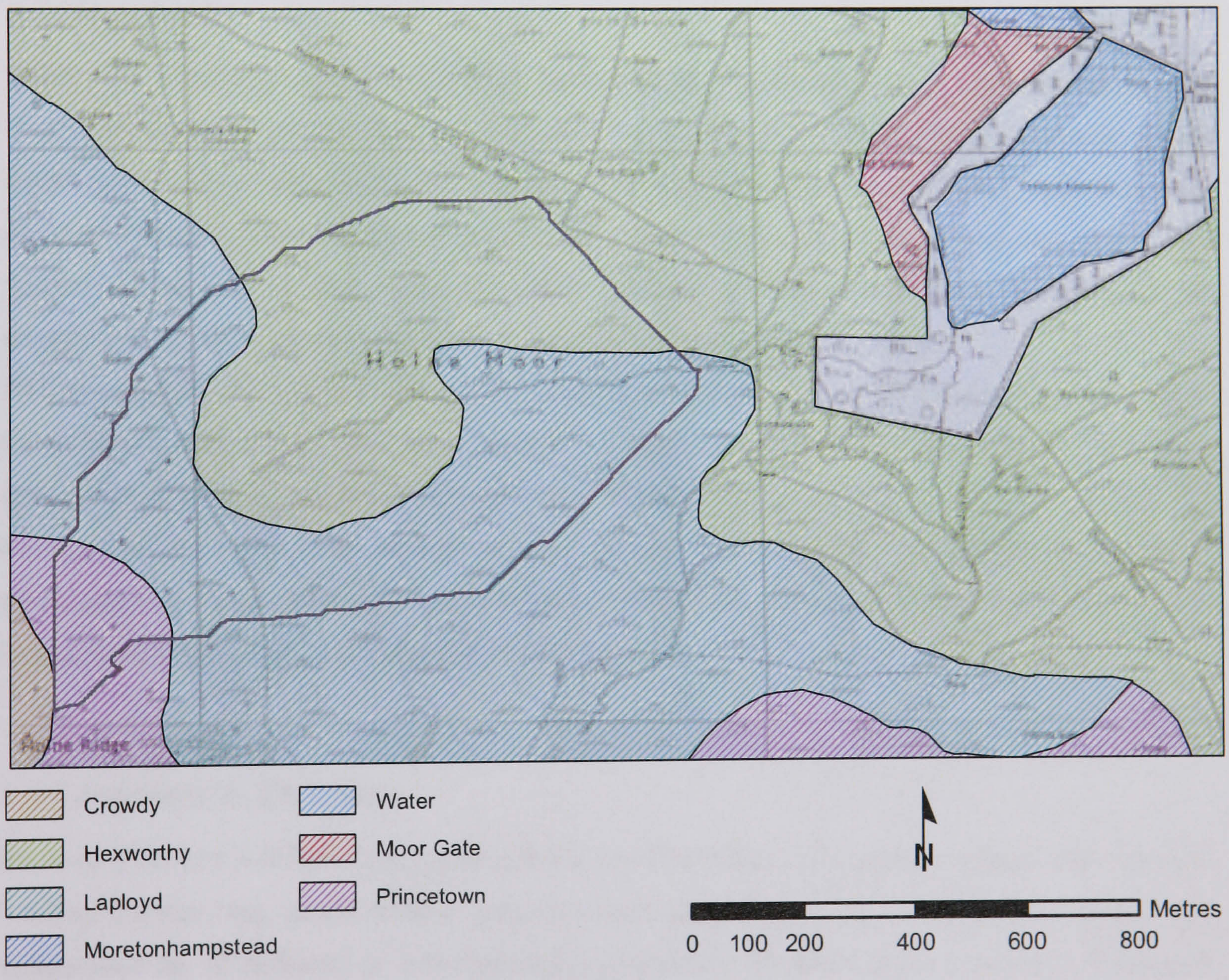


Figure 3.5: Soil map of the Holne Moor around Venford Reservoir. Source: DNPA, 1988, original scale 1:25,000. Background © Ordnance Survey.

The top of the Holne Ridge consists mainly of stagnohumic gleysoils with a peaty topsoil. In the Holne Moor Common area, most of the peat is 40 to 80 cm in thickness and consists mostly of black humified materials. There are some relatively steep slopes. The northern slope, of the Hexworthy association, consists of gritty loams with a wet peaty topsoil, often with a thin ironpan. Part of this association stretches across the river onto the southern slope (Hogan, 1988).

The soils in the study area do not seem to follow the typical Dartmoor soil catena (Section 3.4). However, the soil map of (Fig. 3.5) is on a 1:25,000 scale, which probably does not allow a detailed soil analysis at the hillslope scale. Therefore, this map should be regarded as a reference. Detailed descriptions of the soils in the study area were made in the context of this study and are presented in Chapter 6.

3.7 Vegetation

Within the Dartmoor area vegetation shows subtle changes largely corresponding with micro-climatic differences. Blanket bog can mainly be found on the high plateaux. Grass and heather moors are on the transition from the high ground to the lower, less exposed, dry and better-drained areas (Weaver *et al.*, 1998). The west of Dartmoor has much less heather compared to the more abundant heather growth in the east, because of the distinctively wetter, oceanic weather mainly determined from the west.

The vegetation of Dartmoor is currently semi-natural. Many centuries of land management have resulted into the current vegetation mosaic, which is dependent on the moorland regime of grazing and burning (Weaver *et al.*, 1998).

In this section, the main characteristics of the key habitats are outlined. The most abundant individual species of the habitats, their growing environments and their relation to management actors are described in Section 2.4.

3.7.1 Habitats on Dartmoor

Several different habitats are important for the Dartmoor moorlands: upland and lowland heaths, blanket bog, grass moors (and bracken) and valley mire. All of these habitats are recognised as of national or international importance (English Nature and the Dartmoor National Park Authority, 1997; Fielding and Haworth, 1999). In the Dartmoor Natural Area, the boundaries between upland and lowland heaths are often blurred. An overview of the different vegetation communities on Dartmoor is given in Table 3.1, including the National Vegetation Classification (NVC), and the different extents of the habitats are given in Fig. 3.6.

Table 3.1: The extent of the key moorland habitats of the Dartmoor Natural Area (English Nature and the Dartmoor National Park Authority, 1997). NVC codes are from Weaver et al. (1998) and Rodwell (1991; 1992)

Habitat	NVC code	Main vegetation community	Area (km^2)
Upland heathland	M15	*Scirpus cespitosus – Erica tetralix* wet heath	115
	H12	*Calluna vulgaris – Vaccinium myrtillus* heath	
Lowland heathland	H4	*Ulex galii – Agrostis curtisii* heath	3
Grass moor (and bracken)	U3	*Agrostis curtisii* grassland	53 (49)
	U4	*Festuca ovina – Agrostis capillaris – Galium saxatile* grassland	
	U20	*Pteridium aquilinum - Galium saxatile* community	
Blanket bog	M17	*Scirpus cespitosus – Eriophorum vaginatum* blanket mire	120
Valley mire	M21	*Narthecium ossifragum – Sphagnum papillosum* mire	10

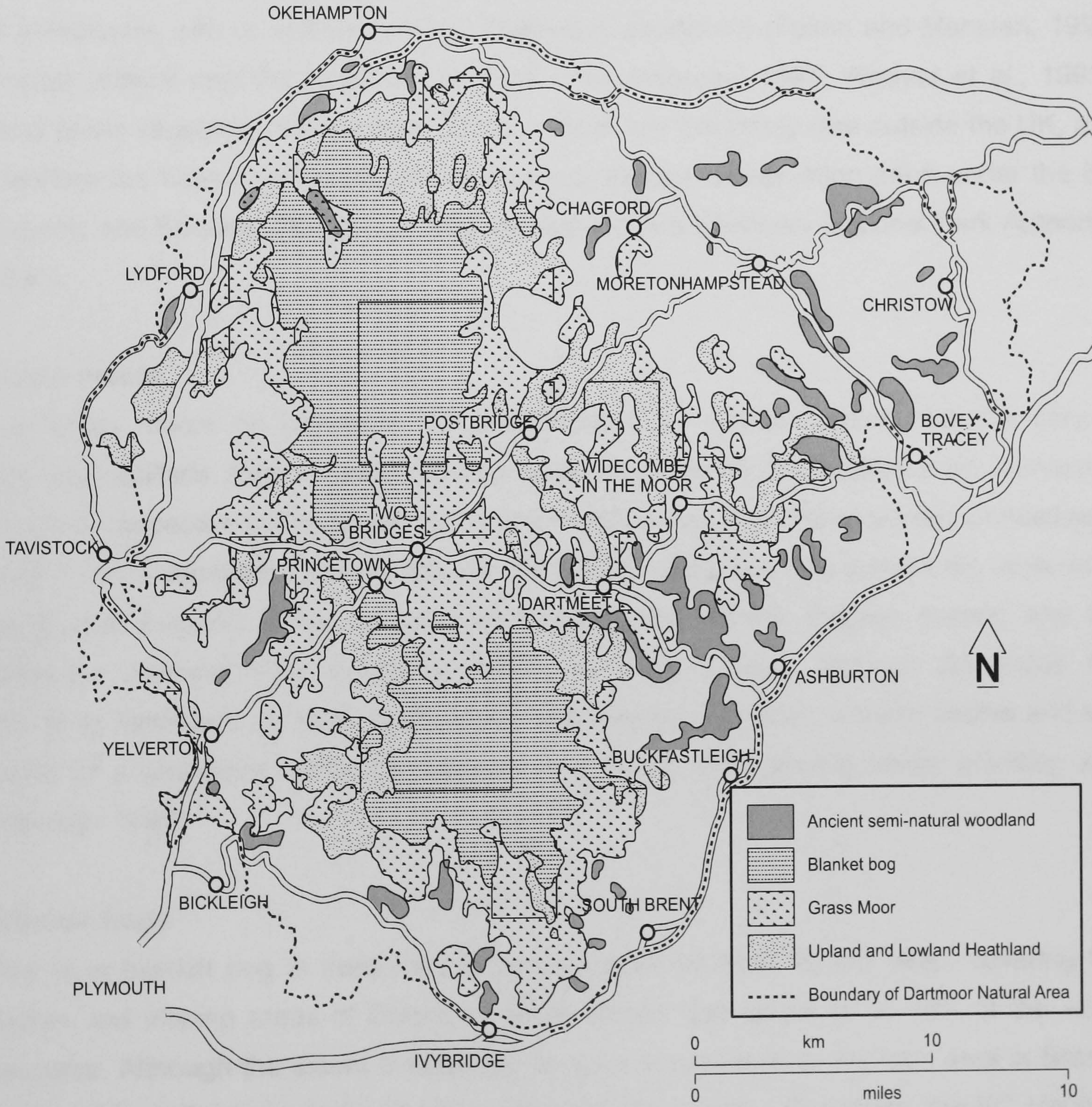


Figure 3.6: The distribution of semi-natural vegetation on Dartmoor (English Nature and the Dartmoor National Park Authority, (1997).

Heathlands

Heaths are defined as a vegetation community with an important, structural role of heather (*Calluna vulgaris*), bilberry (*Vaccinium myrtillus*), cross-leaved heather *Erica tetralix,* and bell heather (*Erica cinerea*) (Fitter *et al.*, 1996). The term 'heather' is also often used to describe this vegetation community (*e.g.* Bardgett *et al.*, 1995). Heathlands are associated with an almost continuous cover of heather. Underneath this cover a variety of other plants (other dwarf shrubs, grasses, sedges, ferns, club-mosses and mosses or lichens) may occur. Trees and tall bushes or shrubs are virtually absent, although there may be some patches of gorse (*Ulex europaeus*), especially on the moors in the Southwest of England, or scattered bushes of juniper (*Juniperus communis*) (Gimingham, 1975).
The heathland habitat is very susceptible to grazing and burning and is declining in favour of grasslands, with or without bracken (*Pteridium aquilinum*) (Felton and Marsden, 1990; English Nature and the Dartmoor National Park Authority, 1997; Weaver *et al.*, 1998). Most of the vegetation communities in this habitat are extremely rare outside the UK, and therefore the habitat is recognised as requiring special conservation effort under the EC Habitats and Species Directive (English Nature and the Dartmoor National Park Authority, 1997).

Grass moors

The grass moors on Dartmoor are characterised by *Festuca ovina*, *Agrostis canina*, *Agrostis capillaris*, *Nardus stricta*, *Juncus squarrosus* and *Molinia caerulea* with increasing wetness, respectively. The grass moors are mainly a result of heavy grazing of heathland areas. Some vegetation communities on the grass moors are rare outside the uplands of Southwest England. Often, bracken is invading the habitat (English Nature and the Dartmoor National Park Authority, 1997). In many places, bracken dominates the Dartmoor landscape as main species in a relatively species-poor, uniform habitat and is a result of a prolonged period of nutrients export and high grazing levels (Fielding and Haworth, 1999).

Blanket bogs

The term blanket bog is used for the layer of peat (at least 50 cm deep) covering the higher, low sloping areas of Dartmoor. Great Britain has about 10 to 15% of the world resource. Although the extent is relatively small in comparison to the total area in Britain, the habitat on Dartmoor is the most southerly of the country. Therefore, the EC Habitats and Species Directive has recognised the habitat as a conservation priority (English Nature and the Dartmoor National Park Authority, 1997). On the blanket bogs, the bog-moss *Sphagnum* and cotton grasses *Eriophorum* spp. are key species, whereas different heather species can be found on the drier mounds (Fielding and Haworth, 1999).

Valley mire

Valley mires mainly occur in valley bottoms along the streams and rivers on Dartmoor. The habitat is characterised by areas of saturated deep peats with acid wetland plant communities. The valley mires on Dartmoor are unique in terms of species composition in Britain, together with the valley mires found on Bodmin Moor. Characteristic for the habitat are cotton-grass, cross-leaved heather and many sedge species (English Nature and the Dartmoor National Park Authority, 1997).

3.7.2 Dartmoor vegetation and management

In a study in the Narrator catchment on south-west Dartmoor, Kent and Wathern (1980) have shown, that *Vaccinium myrtillus* and *Calluna* occur mostly on free draining soils, while *Molinia* dominates wetter soils. Heavy grazing after burning leads via *A. setacea*, which forms a dense cover up to two years after the burn (Kent and Wathern, 1980), to *Agrostis tenuis/Festuca rubra/Festuca ovina* on better soils, and on poorer soils to a combination of *A. setacea* and *Molinia* (Ward *et al.*, 1972). Virtually the entire vegetation composition is altered due to management, except for the wettest areas (*i.e.* blanket bog, valley bog and flushes) (Kent and Wathern, 1980).

In a study by Bunce and Fowler (1989) on the condition of heather in England and Wales, it was shown that on Dartmoor in 1984 the coverage of heather was 14,398 ha in total (15% of the national park). 2,086 ha was dominant and unmanaged (with little burning). *Calluna vulgaris* and other dwarf shrubs of *Erica* represent more than 50% of the vegetation cover; 12,312 ha was sub-dominant, which means that dwarf shrubs of *Erica* are consisting less than 50% of the vegetation cover. There was no occurrence of the so-called 'managed heather', that is heather managed with significant burning. This study was mostly done with the aid of satellite imagery (Landsat), with additional ground survey to assess the quality of the mapping (Bunce and Fowler, 1989).

3.7.3 Vegetation mosaic interactions

From the previous section it can be concluded, that the vegetation mosaics on Dartmoor moorland reflect the combination of climate, topography, soil, hydrology and management. However, in turn vegetation composition also affects soil properties, hydrological pathways and therefore land management to a certain extent.

3.7.4 Vegetation in the study area

On Holne Moor, the extensive amount of peaty topped soils favours vegetation adapted to wet environments, with a relatively large amount of *Molinia caerulea*. The disturbed areas, due to past agricultural practices and tin mining, provide drier soils for the growth of bracken outside the areas directly surrounding the stream (Hogan, 1988). A map produced by English Nature (1994; scale 1:50,000) shows the heather condition distribution on Holne Moor. It is shown that on the higher altitudes, heather is healthy, whereas in the valley bottom, heather is classified as 'slightly overgrazed'. At the lowest areas in the valleys and the area directly surrounding the reservoir, heather is severely overgrazed or not present at all, whereas 'naturally', heather should be present (English Nature, 1994). Figure 3.7 shows the vegetation mosaic from the 1992 air photo. The result of the vegetation survey in the study area is given in Chapter 7.

Figure 3.7: Air photo of the study area in 1992. Source: DNPA.

3.8 Land management on Dartmoor

3.8.1 Grazing

Grazing of the open moorland is controlled within large areas of land known as Commons. About 75 % of the Commons are situated on the north and south moors, the highest plateaux on Dartmoor. Other Common Land is situated more to the eastern fringe of the granite and some smaller areas are found on the western edge (English Nature, 1994). The soils of Dartmoor, when unimproved by ploughing and draining, are mostly unsuitable for arable land and intensive grazing due to excessive wetness (Section 2.7). The vegetation, mostly heath and grasses of low palatability (Section 3.7), dominate the unimproved land and hence do not allow a high grazing pressure. Agriculture is therefore restricted to extensive seasonal grazing. Cattle and sheep graze the land throughout the summer period, but ponies graze on the moors throughout the year (Findlay *et al.*, 1984). Because cattle have to be fed over the winter period, they are removed and taken off the moor by the farmers (Goodfellow, 1998, pers. comm.).

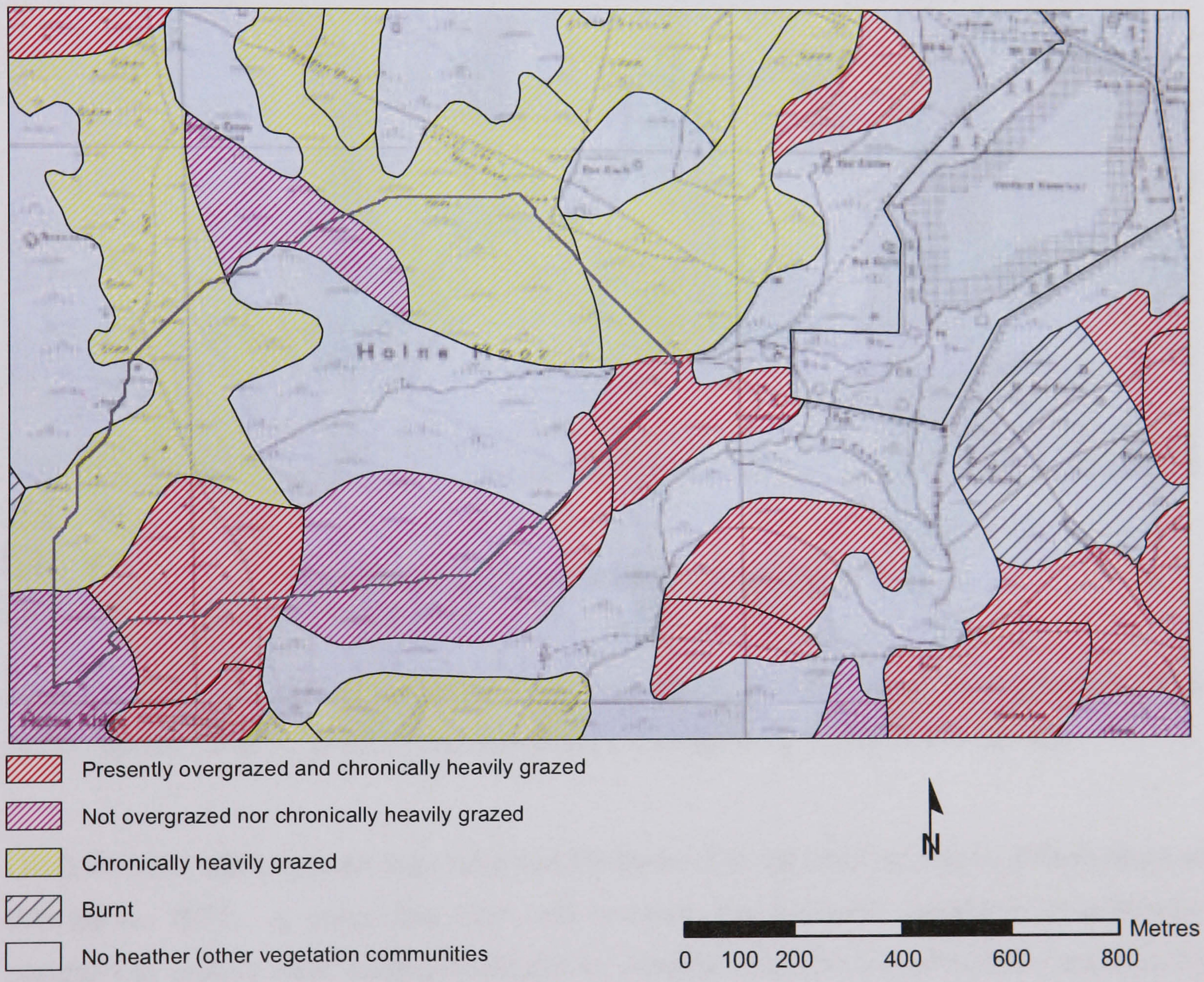


Figure 3.8: Heather utilisation survey 1999 on Holne Moor. Source: DNPA, 1999, unpublished data. Background © Ordnance Survey.

In general, heather conditions on the higher altitudes of the common land are healthy. Closer to the fringes it becomes overgrazed, mainly due to ponies and sheep, but additionally by cattle in places. At the outermost fringes of the commons, there is no heather present at all (English Nature, 1994). Figure 3.8 shows the state of the heather in the study area in 1999, assessed by the Dartmoor National Park Authority on an annual basis (DNPA, 1999, unpublished data).

3.8.2 Burning

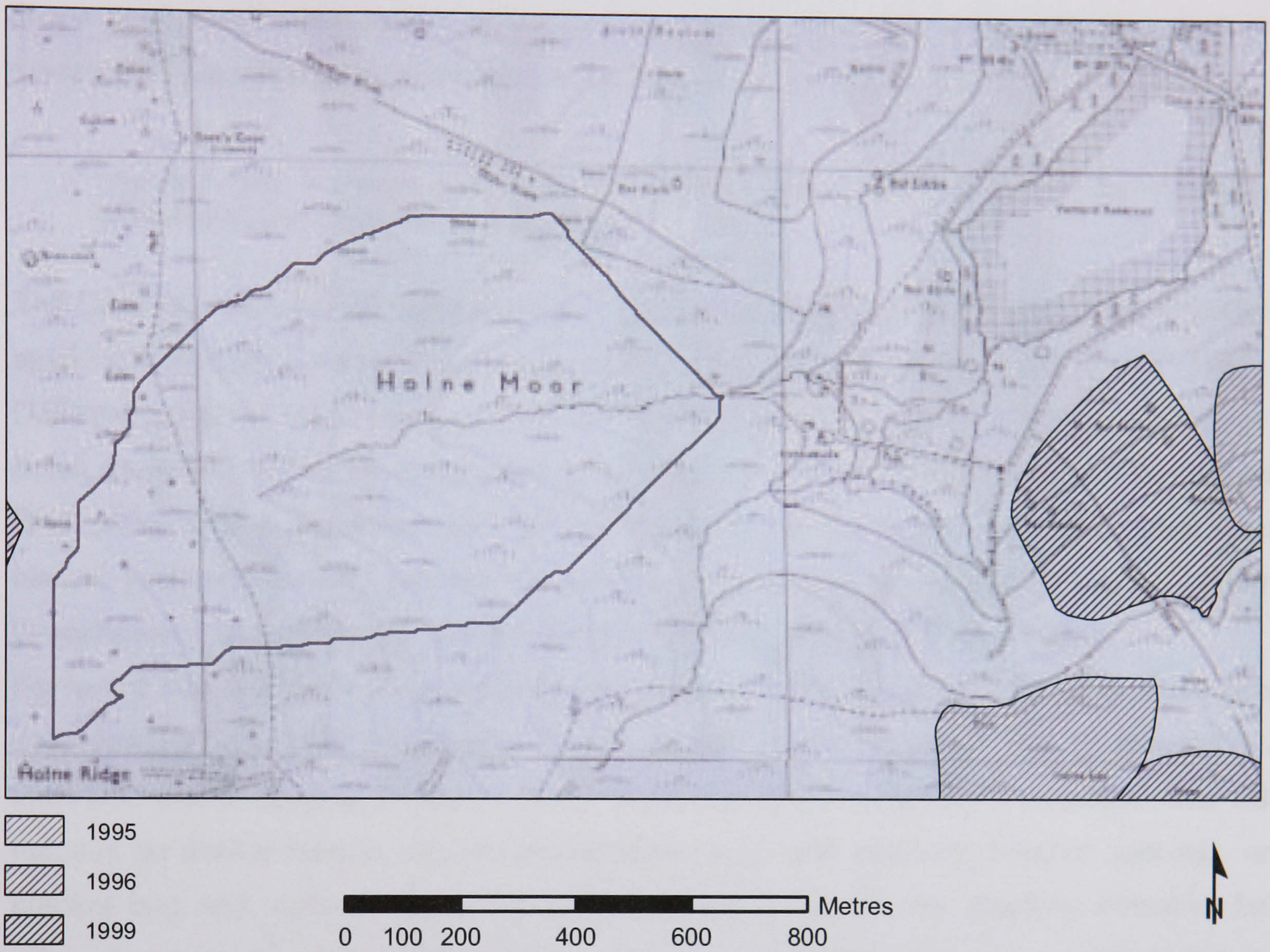


Figure 3.9: Burning history on Holne Moor around Venford Reservoir for the period 1995-2000. Source: DNPA, 2000, unpublished data. Background © Ordnance Survey.

On Dartmoor, burning is an important tool for farmers to control the grazing (Havinden and Wilkinson, 1970). A controlled burn will remove the present vegetation (traditionally heather) to enable new, palatable shoots to develop (Section 2.8). Heather needs to be burned at regular intervals to prevent further succession into woodland (Gimingham, 1975). Nowadays, heather is in decline and farmers burn *Molinia* besides heather (Dartmoor National Park Authority and English Nature, 1997). However, concerns have been raised about the proper annual rotation of the burns. It has been noted, that some area are burned frequently, whereas other areas are rarely burned. On Holne Moor, the area east of the reservoir was burned three times between 1995 and 2000, although this roughly covered different extents (Fig. 3.9). Within the study area, no burns have taken place in the last decade.

3.8.3 The Dartmoor ESA

Since 1997, the Environmentally Sensitive Area (ESA) agreement has been introduced on Dartmoor. This voluntary scheme for farmers (MAFF, 1997; Chapter 1) aims to

> "maintain and enhance the landscape, wildlife and historic values of the areas by encouraging beneficial agricultural practices."

The Dartmoor ESA-agreement, which is also in force on Holne Moor, gives restrictions on stocking densities, burning and cutting of vegetation, livestock feeding, etc. (MAFF, 1997). Different schemes exist for a number of different types of eligible land. On Dartmoor, these types are moorland, permanent grassland, unimproved pasture and enclosed rough land. Additionally, schemes can be implemented for landscape, archaeological and historic features. Farmers can join the scheme, but on the Commons, land can only enter the scheme if all landowners and farmers with grazing rights agree on entering.

For entry into the ESA on moorland, two different entry conditions for moorland were developed, which apply to the type of area studied in this research. Tier 1E focuses on moorland that is covered by semi-natural vegetation and is generally unenclosed. Tier 2B focuses on similar land in suppressed condition (*e.g.* with declining heather species), or blanket bog and lowland heath. Although the tiers have different stocking densities for different moorland areas, within these areas, no distinction has been made between different vegetation types.

In order to provide guidance of maximum stocking rates, MAFF (1994) introduced Livestock Units (LU), which are a method to standardise livestock. These units were combined with their ESA guidelines on Dartmoor (MAFF, 1998).

Livestock Units are calculated by multiplying the headage of each livestock by the following values: each sheep = 0.15 LU; a horse or pony over 6 months old = 1.0 LU, cattle between 6 months and 2 years old = 0.6 LU and older cattle = 1 LU (MAFF, 1994).

On Tier IE and 2B (Table 3.1), stocking rates should not exceed the maximum of 0.04 LU ha^{-1} hardy ponies, both in winter and in summer. Besides the stocking of ponies, an additional 0.225 LU ha^{-1} for Tier 1E (0.17 in Tier 2B) can be stocked in summer. Additionally, farmers must ensure adequate stock management to achieve even grazing over the different moorland types (MAFF, 1997).

Within two years of the implementation of the scheme, farmers must agree on a programme of necessary burning or cutting of the vegetation type to suit the soil and vegetation conditions (MAFF, 1997). This programme is subject to consultation with the various environmental interests as well as land owners and commoners (Crowe, 2002, pers. comm.).

Table 3.2 Maximum grazing limits for moorland entered into the Dartmoor ESA scheme.

Stocking		**Moorland (Tier 1E)**	**Moorland (Tier 2B)**
General		Do not graze so as to cause poaching, overgrazing or undergrazing.	Do not graze so as to cause poaching, overgrazing or undergrazing.
Summer	Ponies	0.04 LU ha^{-1}	0.04 LU ha^{-1}
	Additional	0.225 LU ha^{-1}	0.17 LU ha^{-1}
Winter	Ponies	0.04 LU ha^{-1}	0.04 LU ha^{-1}
	Additional	0.17 LU ha^{-1}	no cattle; 0.08 LU ha^{-1}

Source: MAFF, 1998.

On the Holne Commons, there are 31 commoners involved, of which 10 are grazing commoners. There are also 2 land owners (Crowe, 2002, pers. comm.). The ESA scheme allows a certain degree of flexibility (MAFF, 1997). Therefore, the ESA agreement on the Commons of Holne Moor slightly deviates from the standard guidelines. In this area, Tier 1E was implemented, extended with the so-called Winter Cattle Removal Supplement. This means, that cattle need to be removed from the Commons in the period 1 November to 15 April, which was thought to be having a major effect (Crowe, 2002, pers. comm.).

Moorland entered in the ESA schemes is updated and mapped annually. However, the Foot and Mouth Disease outbreak in 2001 put the update to a low priority. Additionally, there are currently no reports on how the scheme on Holne Moor is implemented, although DEFRA are planning to engage in local monitoring of vegetation change in cooperation with the Dartmoor National Park Authority (Crowe, 2002, pers. comm.).

Although MAFF was recently reorganised and became part of DEFRA (Chapter 2), there has been no change to the Dartmoor ESA scheme. However, DEFRA is currently carrying out a major review of all agri-environmental schemes as part of the Common Agricultural Practice (CAP) review planned for 2003, but it is unlikely that changes will be made to the Dartmoor ESA until at least 2004 (Crowe, 2002, pers. comm.).

Chapter 4: Methodology

4.1 Introduction

The study detailed in this thesis is subdivided into two parts (Section 1.2): first, the baseline hydrological processes that occur in the natural or semi-natural situation, and second, the impacts of grazing and burning on the soil and hydrology. The methodology used in the research and described in this chapter is therefore organised in the same manner.

- In Section 4.2, stream discharge and rainfall measurements are described.
- Section 4.3 and 4.4 deal with soil moisture measurements at the hillslope scale, including environmental variables that may play a role in soil moisture and soil moisture dynamics.
- Section 4.5 focuses on the plot scale and the soil water pathways on different positions on the hillslope.
- Section 4.6 describes the digital data in a GIS at the catchment scale available from other sources.
- The last two sections of the chapter, Section 4.7 and 4.8, deal with the burning and grazing experiments, respectively.

4.2 Rainfall-runoff response and catchment hydrology

Data on rainfall and streamflow were required to analyse the hydrological conditions at the catchment scale, including discharge and flow duration characteristics. River stage levels were recorded at two locations (Fig. 4.1), in a headwater catchment (12.1 ha, Plate 4.1) and at the outlet of the whole watershed (61.0 ha). A stage-discharge relationship was determined for each site. Rainfall was recorded at a single location within the watershed. This section will outline these hydrological recordings and details the field calibrations.

4.2.1 Stream flow gauging at the headwater catchment

At the upper or headwater catchment (Fig. 4.1), stream discharge levels were estimated to be relatively small. Sediment movement in the stream was evident, but not large enough to adversely affect stage recordings in the short term of the research. The length profile of the stream at this site showed a relatively steep gradient and therefore, conditions were suitable for the installation of an aluminium thin-plate V-notch weir (Newson, 1994; Shaw, 1994; Plate 4.1).

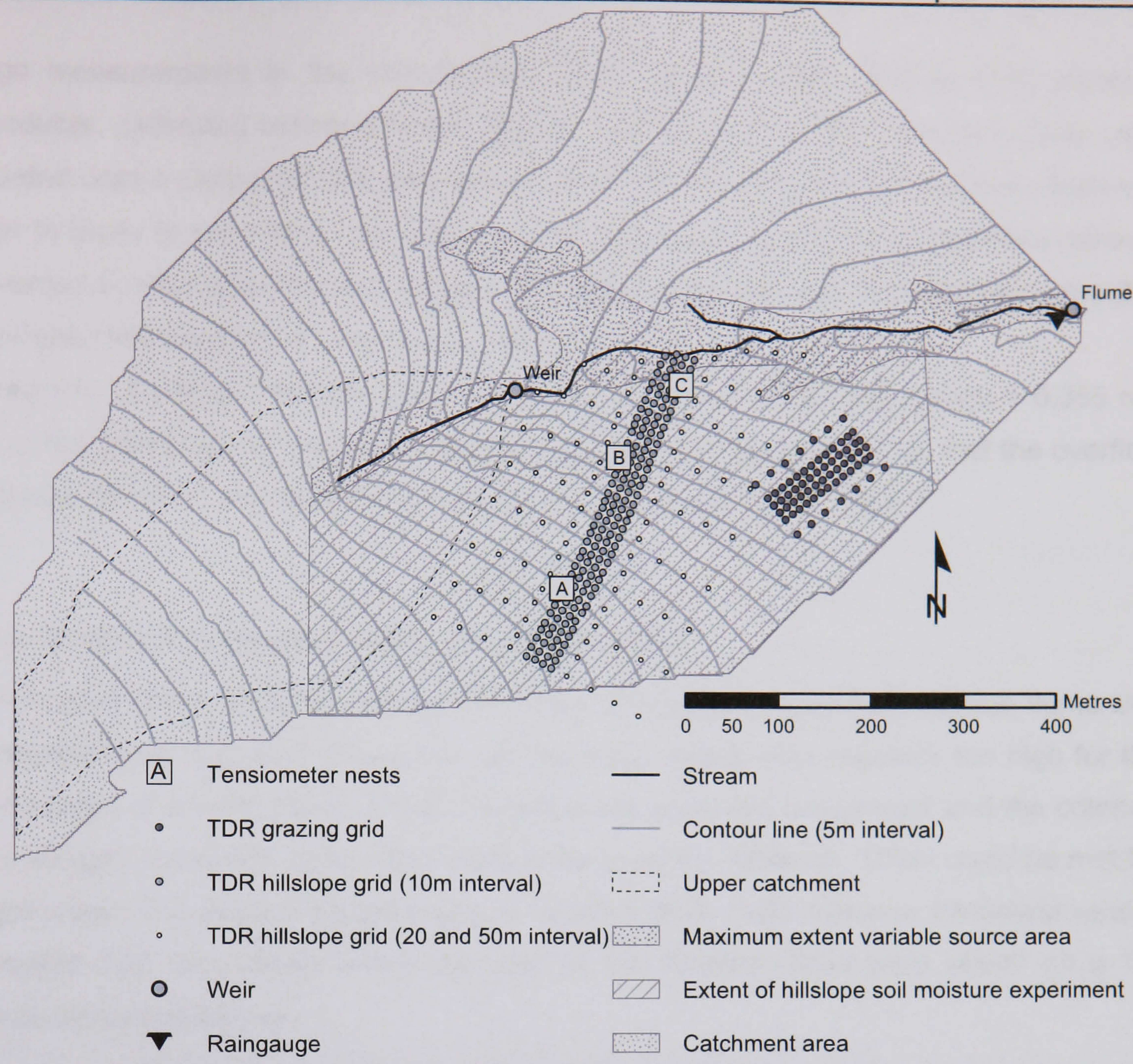


Figure 4.1: Map of the study area with experiment locations as described in this chapter.

Plate 4.1: The thin-plate weir.

Stage measurements in the stream were taken using a Druck PDCR 1830 pressure transducer, calibrated between 0 and 100 cm water column in the laboratory. Data were recorded onto a Campbell 21X data logger. A 15-minute recording interval was chosen in order to study to the river's fast rainfall-runoff response. Limited access for data retrieval prevented shorter time intervals. Stage recordings at the weir took place between the 20th November 1998 and the 4th November 1999.

During the 12-month recording period, the weir overflowed five times (stage > 0.355 m), due to the flashiness of the stream. Calibrations showed (Section 4.2.3), that the overflow level was 89.8 l s^{-1}, expressed in discharge per unit area as 2.66 mm hr^{-1}.

4.2.2 Stream flow gauging at the catchment outlet

At the outlet of the whole catchment (61.0 ha), a fibreglass trapezoidal Lothian flume with a concrete base was built (Plate 4.2), as discharge levels were regularly too high for the construction of a weir (Shaw, 1994). Flumes avoid sediment entrapment and the criterion for a straight channel in combination with a low gradient (Newson, 1994) could be met for construction. For stage measurements, a Druck PDCR 1830 pressure transducer and a Campbell 21X data logger were also used at this location. Data were stored on a 15-minute recording interval.

Plate 4.2: The Lothian flume at the catchment outlet.

Measurements at the flume were taken between the 10th December 1998 and the 9th June 2000. Although the flume was extended to enable high peak discharges measurements, the flume occasionally overtopped, with a maximum recording level of 930 l s^{-1}, equivalent to 5.5 mm hr^{-1} (discharge per unit area). Field stage and discharge measurements were carried out to convert the stage recordings into discharge, described in the next section.

4.2.3 Stage - discharge calibrations

Field discharge measurements

Field measurements of discharge at both sites were carried out at several occasions to cover different stage levels. These measurements were used for comparison of the standard equations (weir site) or the manufacturer's specifications (flume site) to discharge levels as measured in the stream. Two methods were chosen to facilitate the calibrations.

Firstly, several velocity measurements using a current meter were carried out in several sections within the cross-sectional area of the stream, calculating the discharge by using the velocity and cross-sectional areas of the different sections (Newson, 1994; Shaw, 1994). This was carried out at different locations between 2 and 10 m upstream of each of the stream gauges.

Secondly, a dilution gauge (constant concentration method) was used, in which a tracer with a known concentration of solutes was added to the stream. In this case, ordinary kitchen salt, NaCl, was used, in order to avoid contamination of the drinking water in the reservoir at the catchment outlet. Downstream, over such a distance that full mixing could be assured in the turbulent stream, the concentration of solutes in the stream was measured after equilibrium was reached (Shaw, 1994). The concentrations were measured electronically with a conductivity meter. The discharge could then be calculated by using Equation 4.1 (Shaw, 1994):

[4.1] $$Q = \frac{c_1 - c_2}{c_2 - c_0} q$$

where:

Q = stream discharge (l s^{-1});

c_0 = stream background concentration (g l^{-1});

c_1 = tracer concentration (g l^{-1});

c_2 = final concentration in well-mixed flow (g l^{-1});

q = rate at which tracer is added to stream (l s^{-1}).

Weir calibration

Calculation from stage to discharge at the weir site was achieved by using a standard equation for thin plate V-notch weirs (Brater and King, 1976; Equation 4.2):

[4.2] $$Q = \frac{8}{15} * \sqrt{2g} * Cd * \tan\frac{\beta}{2} * h^{2.5}$$

where:

Q = discharge (m^3 s^{-1});

h = head (m) (< 0.355 m);

g = gravitational constant (9.81m s^{-2});

β = angle of V-notch (60°);

Cd = constant (0.576 if β = 60°, Brater and King, 1976).

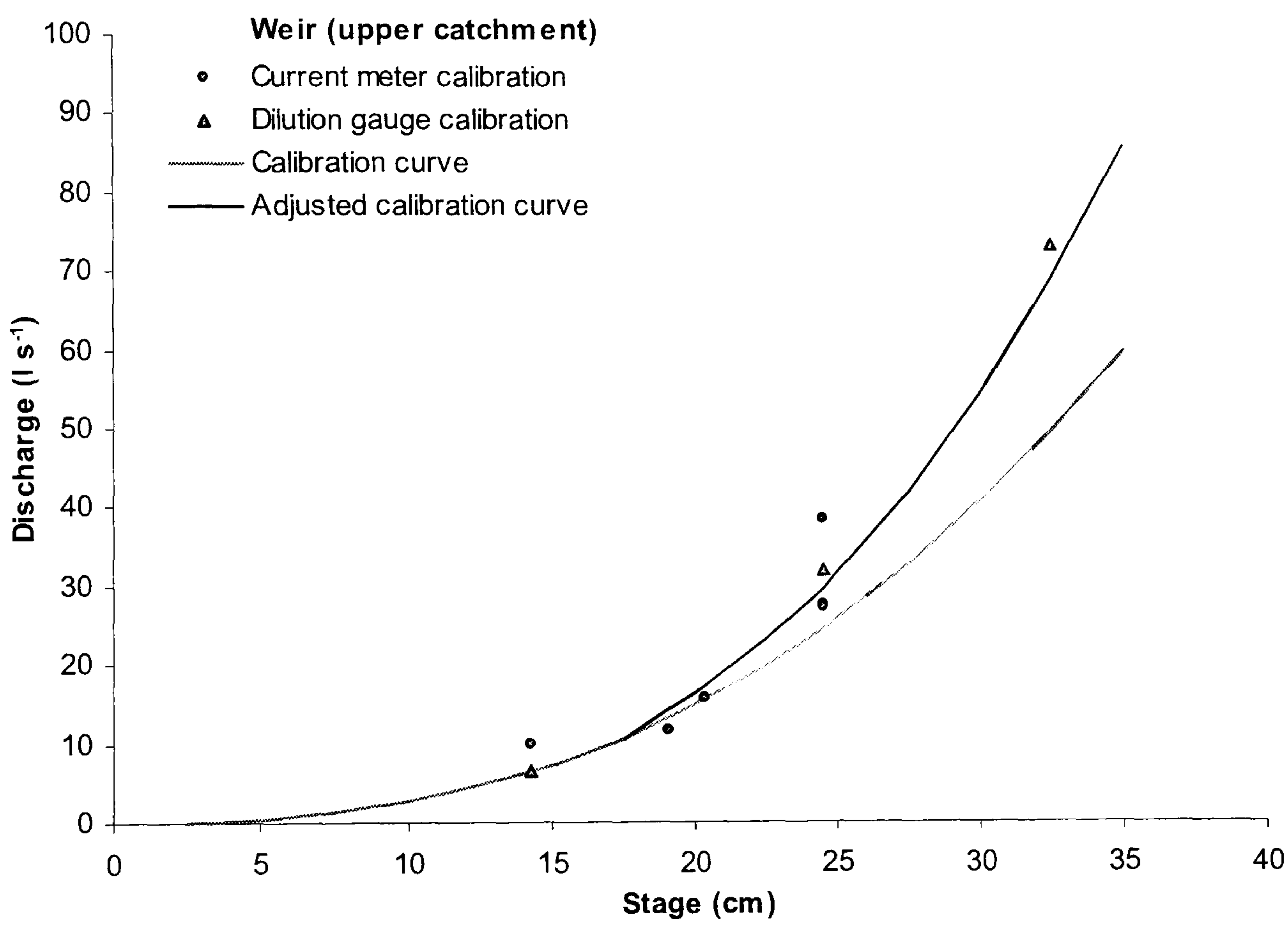


Figure 4.2: Calibration curves of the stage-discharge relationship of the V-notch weir based on Equations 4.2 (grey) and 4.3 (black).

Figure 4.2 shows the calibration curves for the stage-discharge relationships for the V-notch weir. At low flow, the calibration curve and the field measurements correspond well. At higher discharge levels, above a stage level of about 17.5 cm, the calibration appeared less precise.

Due to the flashy nature of the stream only one field reading at near maximum weir capacity was obtained. During this field visit, it was observed that stage levels were relatively insensitive for water level fluctuations induced by turbulence, which at the highest recorded discharge in the field showed an error of about ± 0.2 cm (equivalent to about 1 l s^{-1}). Therefore, the error could not be attributed to measurement inaccuracy. Instead, for stage levels between 17.5 and 35.5 cm, an adjusted (empirical) equation was used (Equation 4.3):

[4.3] $$Q = \frac{(0.2 * h^3 + h)}{100} \qquad (R^2 = 0.96)$$

where:
Q = discharge (m^3 s^{-1});
h = stage (m), where $0.175 < h < 0.355$ m.

Flume calibration

At the flume site, discharge was calculated from the stage by using four different formulas for four separate stage sections. Two sections were covered by the fibreglass part of the flume, from h = 0 to 0.25 m and 0.25 to 0.31 m (Figure 4.3). The Equations 4.4 and 4.5 were derived from calibration carried out using non-linear regression on the data provided by the flume manufacturer. These formulae showed a significant correlation (R^2 = 0.98) to known data points. However, the flashy nature of the stream required measurements above this level. The stage-discharge relationship was extrapolated to this height and adjusted for a wider (Section 3) and narrower section (Section 4), yielding Equations 4.6 and 4.7.

[4.4] Section 1: $Q = 1014.4\, h^2 - 23.886\, h + 0.7312$

[4.5] Section 2: $Q = 1492.4\, h^{2.3385}$

[4.6] Section 3: $Q = 694.634\, h^2 - 463.8677\, h - 113.997$

[4.7] Section 4: $Q = 6268.853\, h^2 - 2716.96\, h + 308.998$

where:
Q = discharge (m^3 s^{-1});
h = stage (m).

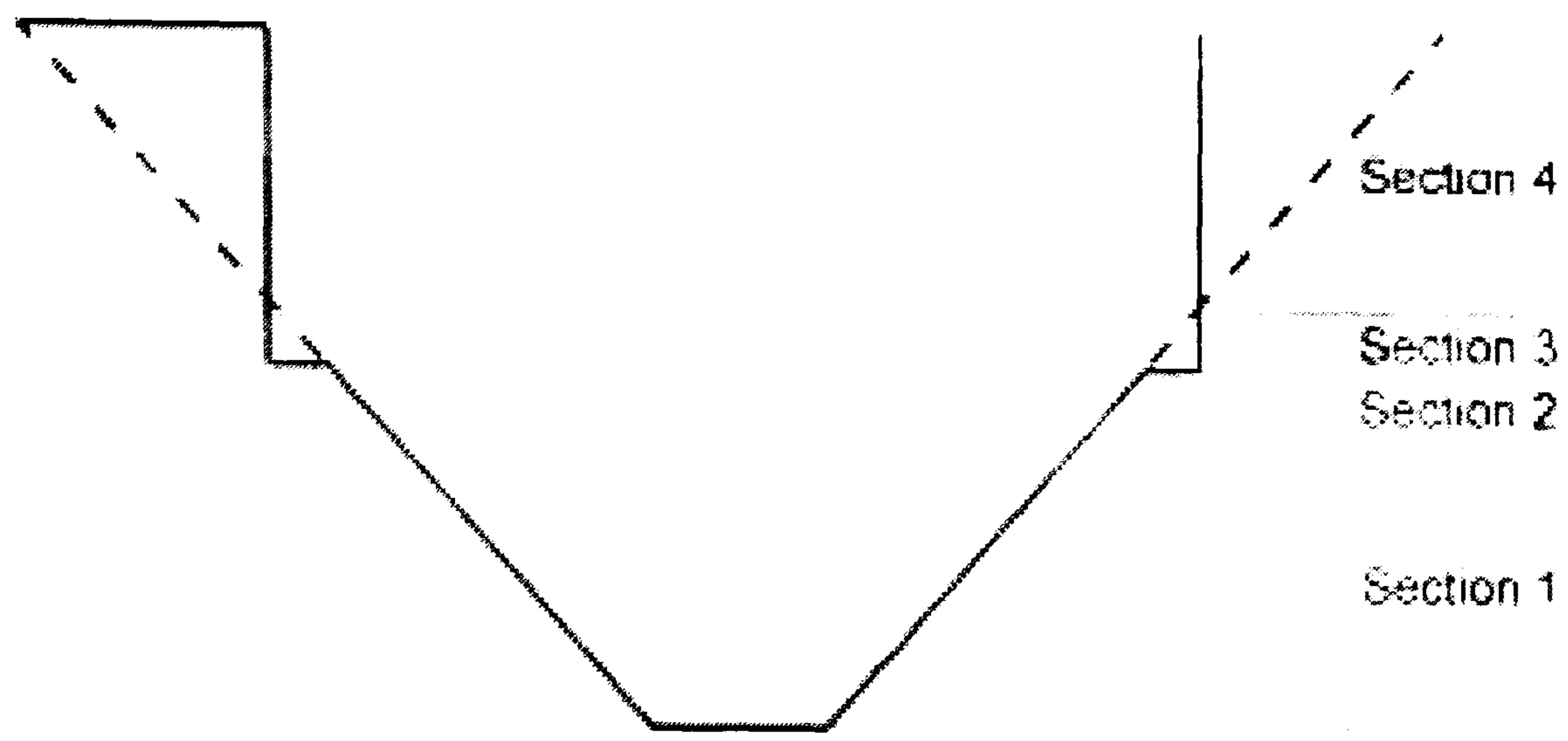


Figure 4.3: Cross-section of the flume with the four different stage sections.

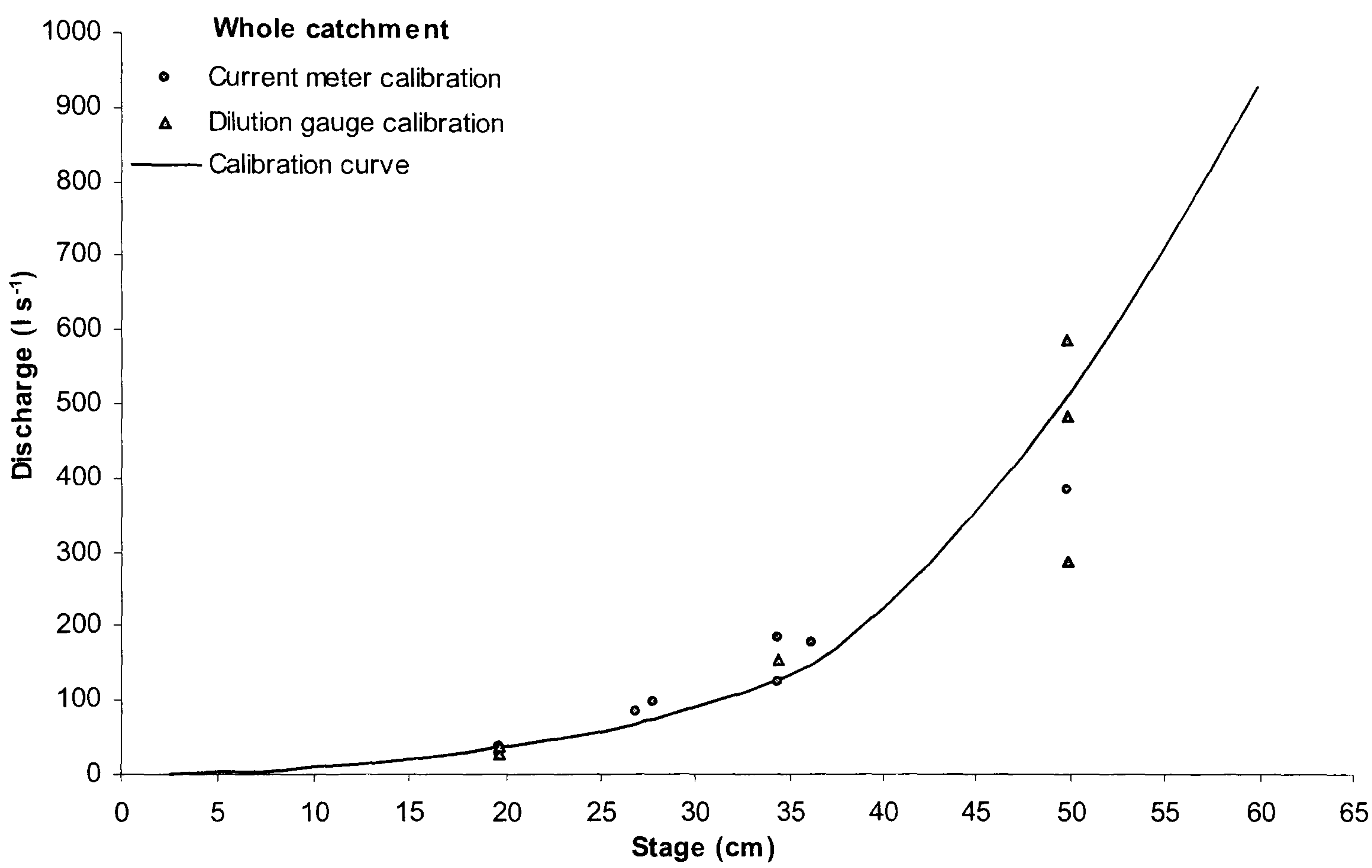


Figure 4.4: Calibration curve of the stage-discharge relationships at the flume based on Equations 4.4 to 4.7.

Figure 4.4 shows the calibration curve for the flume site. A regression with the discharge data obtained in the field showed an R^2 of 0.86. Especially at low discharge levels, the curve corresponds well with the field data. At higher levels, the calibration appears less precise. However, the error involved in the stage level measurements becomes increasingly more important. It has been noted in the field, that at such high levels, stage measurements can incorporate an error of ± 2 cm due to increased water turbulence, which means an error of ± 70 l s^{-1}. This explains the larger variation during high discharge conditions.

4.2.4 Rainfall measurements

The raingauge was positioned at an altitude of 340 metres adjacent to the flume (Fig. 4.1). Sumner (1988) suggested a minimum number of five gauges per 100 km^2 for monthly readings. Shaw (1994) recommended a single raingauge for recordings on a daily basis for moorland catchments smaller than 2 km^2 in Britain. The relatively small area of the watershed (0.61 km^2) justified rainfall recordings with a single gauge, although measurements were taken on a more detailed time scale.

Rainfall measurements were carried out using a tipping bucket (0.2 mm per tip), installed at approximately 80 cm above the surface. The Meteorological Office standards requires 30 cm height for non-recording rain gauges, but specifies that for recording gauges, the height is usually greater (Meteorological Office, 1981). For the tipping buckets specified, a height of 45 cm is recommended. Although the raingauge in the study area was installed higher, this was the best possible option in order to protect the raingauge against livestock (Plate 4.3). Although rainfall measurements were probably more representative nearer the centre of the catchment, this position was chosen because of the proximity to the logger used for stage recordings at the flume.

Plate 4.3: The raingauge with protection frame.

Rainfall tips were recorded in one-minute intervals. A wooden frame was built directly around the gauge to protect from livestock, after the first device was damaged and had to be replaced. Although the shape of the raingauge was specifically designed to minimise wind effects, rain gauges from this type are known to slightly underestimate rainfall at ground level. Duchon and Essenberg (2001) for example showed that this might be up to 4% of undercatch for a tipping bucket rain gauge, unprotected to the wind in comparison to a rainfall pit at ground level. Section 5.2 provides a more detailed discussion on the spatial distribution of rainfall due to wind and altitude variability.

In order to estimate the systematic errors involved and to analyse the altitude effect (Newson, 1976; Chapell, 1990), rainfall data were compared to data obtained from two other rain gauges (Fig. 4.5) in the direct vicinity of the watershed, operated by South West Water. One of these gauges was positioned close to Venford reservoir at an altitude of 290 meters above sea level. This gauge was read on a daily basis. A second gauge was located on the plateau at Ryder's Hill, 2500 meters southwest from the watershed raingauge at an altitude of 500 m. This gauge was only measured monthly, but was the only other reference available and facilitated comparison on a monthly basis.

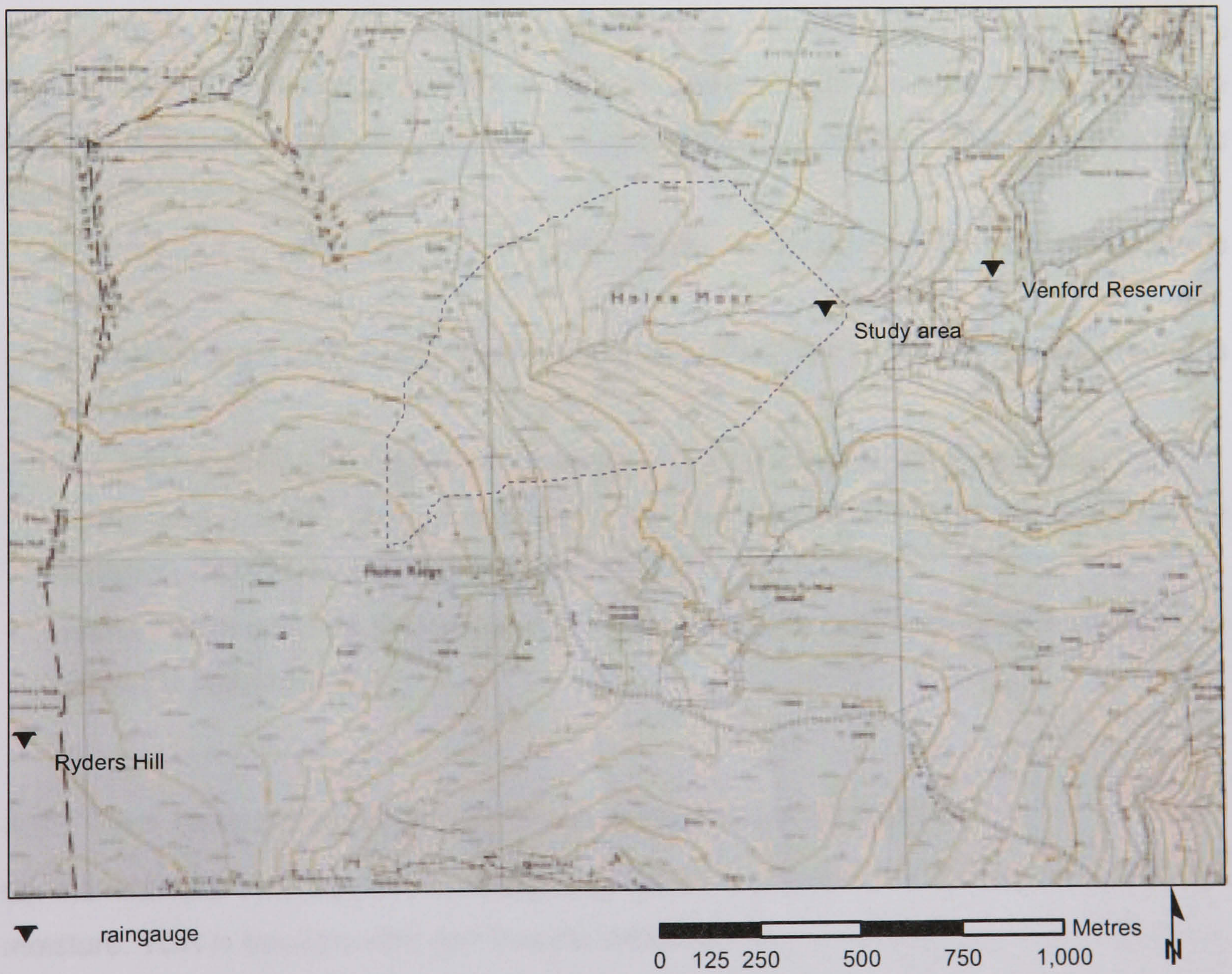


Figure 4.5: Rain gauge locations in and near the study area.

4.2.5 The Narrator data set

Rainfall records from a weather station in the Narrator catchment, situated near Burrator reservoir in the southwest of Dartmoor were used occasionally to supplement data from Holne Moor. This catchment has been monitored since the 1970s (Solman, 1999, pers. comm.). A correlation analysis of rainfall data between the study catchment and Narrator was carried out and then extrapolated for use within the Holne Moor watershed. Air temperature was also measured at this site and corresponded well with temperature measurements taken at the tensiometer loggers (Section 4.5) and could therefore be used to fill data gaps at the study catchment.

4.3 Soil moisture variability at the hillslope scale

Many researchers have shown, that soil moisture and soil moisture variability is an important factor for soil water transport on the hillslope scale (*e.g.* Gurnell, 1981; Grayson *et al.*, 1997; Fitzjohn *et al.*, 1998; Western *et al.*, 1999; Section 2.5). Therefore, a measuring grid at the hillslope scale in order to study spatial and temporal soil moisture patterns in different wetness conditions. A non-destructive set-up was established using Time Domain Reflectometry.

- In Section 4.3.1, the principle of Time Domain Reflectometry and the calibration is outlined;
- In Section 4.3.2, calibration of the thetaprobe (Frequency Domain Reflectometry) is explained;
- In 4.3.3, the set-up and layout of the hillslope soil moisture grid is described;
- Section 4.3.4 details the experiment to test the representativity of the soil moisture hillslope grid in comparison to the entire hillslope;
- Section 4.3.5 explains the layout of a similar TDR grid in a more heavily grazed area within the watershed.

4.3.1 Time Domain Reflectometry measurements and calibration

On the hillslope, Time Domain Reflectometry (TDR) was used to determine volumetric soil moisture. TDR is based on the fact that the dielectric constant of the soil is sensitive to the soil water content, but relatively insensitive to variations in bulk density, temperature, salinity and mineral composition (Topp *et al.*, 1980). Therefore, a simple empirical relationship can be established between the apparent dielectric constant and the volumetric water content of the soil, measured through two or three stainless steel rods inserted into the soil (Topp *et al.*, 1980). Operationally, the rods function as a wave-guide of an electromagnetic pulse from a cable tester. When the pulse reflects at the end of the wave-guides, part of the energy is reflected back to the cable tester. The time it takes to reflect back is a measure for the dielectric constant of the soil (Topp *et al.*, 1980; Nielsen *et al.*, 1995), and therefore a measure of soil moisture. Knight (1992) recommended that the ratio rod thickness / distance needs to be at least 0.1 to avoid a certain 'skin effect'. He showed, that most of the sensitivity is close to the rods if the rod diameter is small compared to the distance. If air gaps occurred close to the rods, significant errors could occur (Knight, 1992).

However, research by Jacobsen and Schjønning (1993) has shown, that texture, bulk density and organic matter content can affect TDR measurements, but the influences of these soil characteristics are relatively small in comparison to the uncertainty in the determination of the dielectric constant of the soil. Roth *et al.* (1992) showed, that the dielectric constant-soil moisture relationship did differ significantly only when soils of very different compositions were used. He showed that this was not significant enough to individually calibrate them if the error of margin of a standard deviation of 0.015 $cm^3\ cm^{-3}$ would be acceptable, which is twice the error margin of Topp *et al.* (1980). Roth *et al.* (1992) also showed that measurements are not affected by soil texture or structure.

However, Topp *et al.* (1980) indicated, that there is a significant difference in the relation between the dielectric constant and soil moisture if different soils have a large difference in organic matter content. Therefore, they suggested that different calibration curves should be used for mineral and organic soils. Several authors have established calibration curves between the dielectric constant and soil moisture for organic soils (*i.e.* Topp *et al.*, 1980; Pepin *et al.*, 1992; Roth *et al.*, 1992). Roth *et al.* (1992) concluded, that if an absolute error of less than 0.035 $cm^3\ cm^{-3}$ is acceptable, then one single calibration curve could be used for organic soils. Equation 4.8 gives their proposed calibration:

$$[4.8] \quad \theta = -2.33 \times 10^{-2} + 2.85 \times 10^{-2} K - 4.31 \times 10^{-4} K^2 + 3.04 \times 10^{-6} K^3$$

where:
θ = volumetric soil moisture content ($cm^3\ cm^{-3}$);
K = dielectric constant (-).

In order to calibrate the TDR with a Dartmoor soil, a plastic cylinder (105 mm diameter, height of 225 mm) was used to extract a soil core from the field. Baker and Lascano (1989) showed, that the influence is negligible beyond a diameter twice the rod spacing, and does not extend deeper than the rod length. The volume chosen was as small as possible, without disturbing the sphere of influence of the TDR-rods. 5 mm rods were used, with a length of 200 mm and a spacing of 50 mm. The soil core was brought back into the laboratory and saturated from the bottom upwards to expel the air. Then, two TDR waveguides were installed, similar to the ones used on the hillslope (next section). TDR readings were taken on an hourly basis in the beginning, and were then reduced to a daily interval, with decreasing soil moisture content. The soil core was weighed when the dielectric constant was recorded. After the measurements, the dry bulk density was established by removing the material from the core, placing it in the oven at 105° for 48 hours to dry (Rowell, 1994) and then weighing the solid fraction. The soil moisture – dielectric constant values were then plotted against each other and compared to calibration curves for organic soils established by Topp *et al.* (1980), Pepin *et al.* (1992) and Roth *et al.* (1992), shown in Fig. 4.6. A regression analysis, following the same formula as Topp *et al.* (1980), Pepin *et al.* (1992) and Roth *et al.* (1992) yielded Equation 4.9:

$$[4.9] \quad \theta = -6.774 \times 10^{-3} + 4.502 \times 10^{-2} K - 1.632 \times 10^{-3} K^2 + 2.4 \times 10^{-5} K^3 \quad (R^2 = 0.981)$$

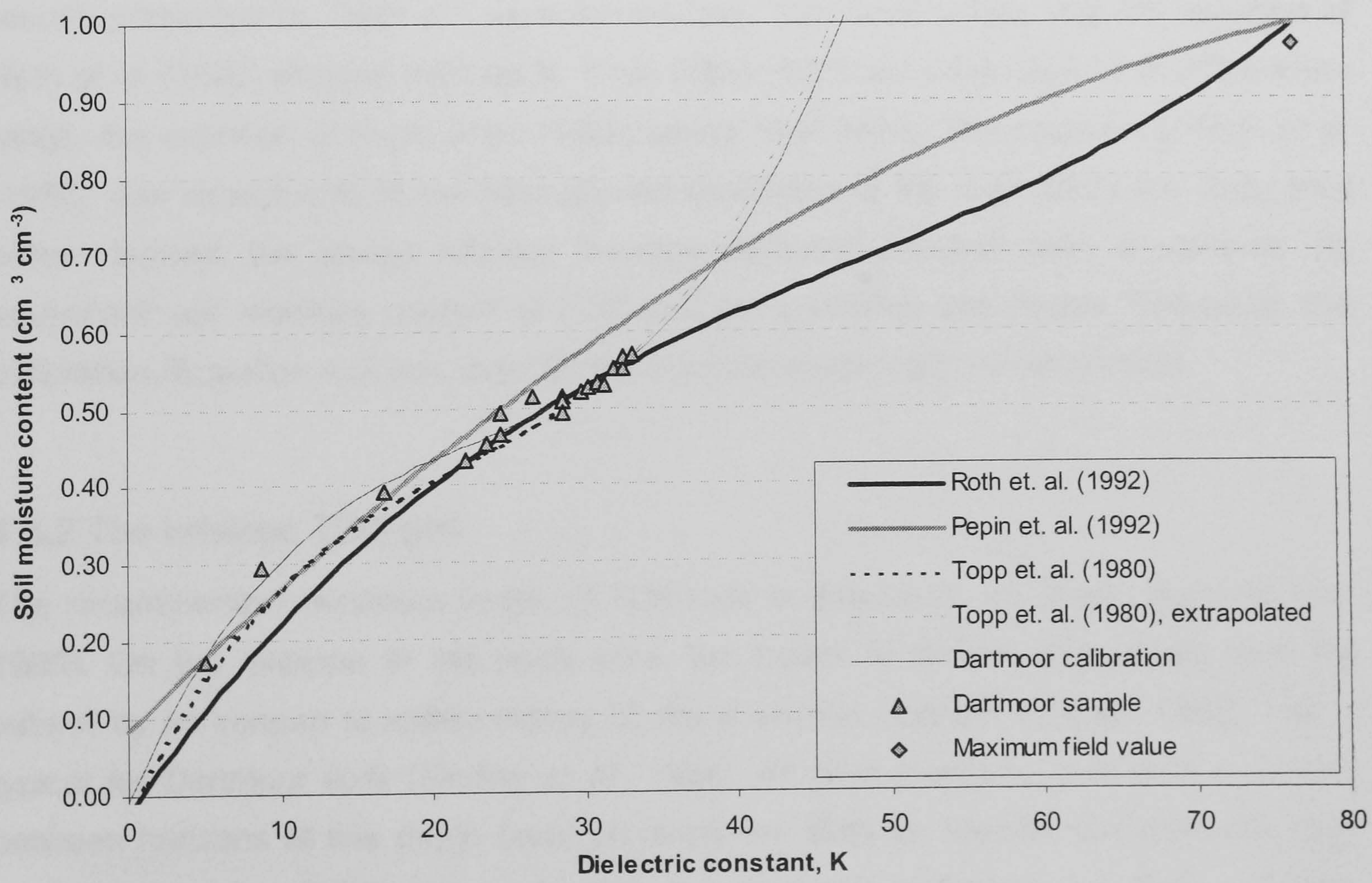


Figure 4.6: TDR calibration curves.

Although the fit was highly significant, this was only in the 0.20 – 0.55 cm^3 cm^{-3} range, similar to the findings of Topp *et al.* (1980). According to Equation 4.9 the highest field recording yielded soil moisture values as high as 4.64 cm^3 cm^{-3}, higher than pure water. It was also realised that many dielectric constant readings in the field were higher than the equivalent of 0.55 cm^3 cm^{-3}, necessitating calibration between 0.55 cm^3 cm^{-3} and saturation.

The recording with the highest dielectric constant value was taken in saturated conditions, with water standing on the soil surface. The porosity of this sample point, in a moss peat soil near the stream was measured (Section 4.4) and was the highest found in the study area, about 0.96 cm^3 cm^{-3}. Several authors have found similar porosity values for organic soils (Munro, 1982; Pepin *et al.,* 1992; Roth *et al.,* 1992). Therefore, this value could be added to the graph as a guideline (Fig. 4.6).

Table 4.1: Goodness-of-fit of the different TDR calibration curves

Author	R^2, without extreme value	R^2, with extreme value
Topp *et al.* (1980)	0.953	(negative)
Pepin *et al.* (1992)	0.790	0.903
Roth *et al.* (1992)	0.894	0.950

When comparing all three equations, with and without the extreme value found in the field, results presented in Table 4.1 were established. This table shows that the equation of Roth *et al.* (1992) showed the best fit. From Figure 4.6 it can be deduced that in the lower range, the equation of Pepin *et al.* (1992) seems to fit better. The equation of Roth *et al.* (1992) was expected to fit the naturally wet conditions of the soils within the study area better. Indeed, the lowest hillslope average dielectric constant (with a value of 18, equivalent soil moisture content of 0.37 cm^3 cm^{-3}) justified this choice. Therefore, this calibration (Equation 4.8) was used for the volumetric soil moisture calculations.

4.3.2 The hillslope TDR grid

The recommended minimum length of TDR-rods is around 10 cm (Baker and Lascano, 1989). On the hillslope in the study area, the topsoil is divided distinctively from the subsoil by an ironpan at approximately 30 cm at several locations (Hogan, 1988). This is typical for Dartmoor soils (Findlay *et al.*, 1984). At other locations, a division in texture between horizons at this depth could be observed. Both an ironpan and a texture jump could be important barriers for soil water. It was shown in Section 2.4, that in general terms, most of the vegetation roots can be found in the top 20 to 30 cm. It was expected that the influence of land management on the soil hydrology would be mainly via a change in vegetation. It was therefore assumed that rods of 20 cm in length would give a good representation of the soil moisture content of the topsoil.

At the hillslope scale, on the north-facing hillslope within the watershed, a permanent rectangular grid of TDR rods was constructed. Stainless steel rod pairs (151 pairs in total, 20 cm long, 5 mm diameter, spacing 5 cm) were inserted vertically in the soil with a ten-by-ten metre spacing in a 400 by 30 m grid (Figs. 4.1 and 4.7). Webster and Oliver (1992) showed that in soil surveys, 150 sample points are usually enough to get a reasonable semivariogram estimate for a geostatistical analysis. Measurements were taken with a Tectronix 1502B cable tester approximately every fortnight, but were reduced depending on weather conditions later on in the project to cover a wide range of soil moisture conditions. In total, measurements were taken on 19 occasions. On each occasion all measurements were recorded in a two to four hour period.

In order to increase lateral coverage on the hillslope, two transects at 20 m intervals were established at a distance of 20 m from the grid, as well as a 30 x 50 m grid (Fig. 4.7). Exact locations of the nodes were achieved by surveying using a Zeiss electronic distance meter (EDM), combined with GPS (Global Positioning System) measurements to enable geo-referencing of the grid, using a Garmin GPS.

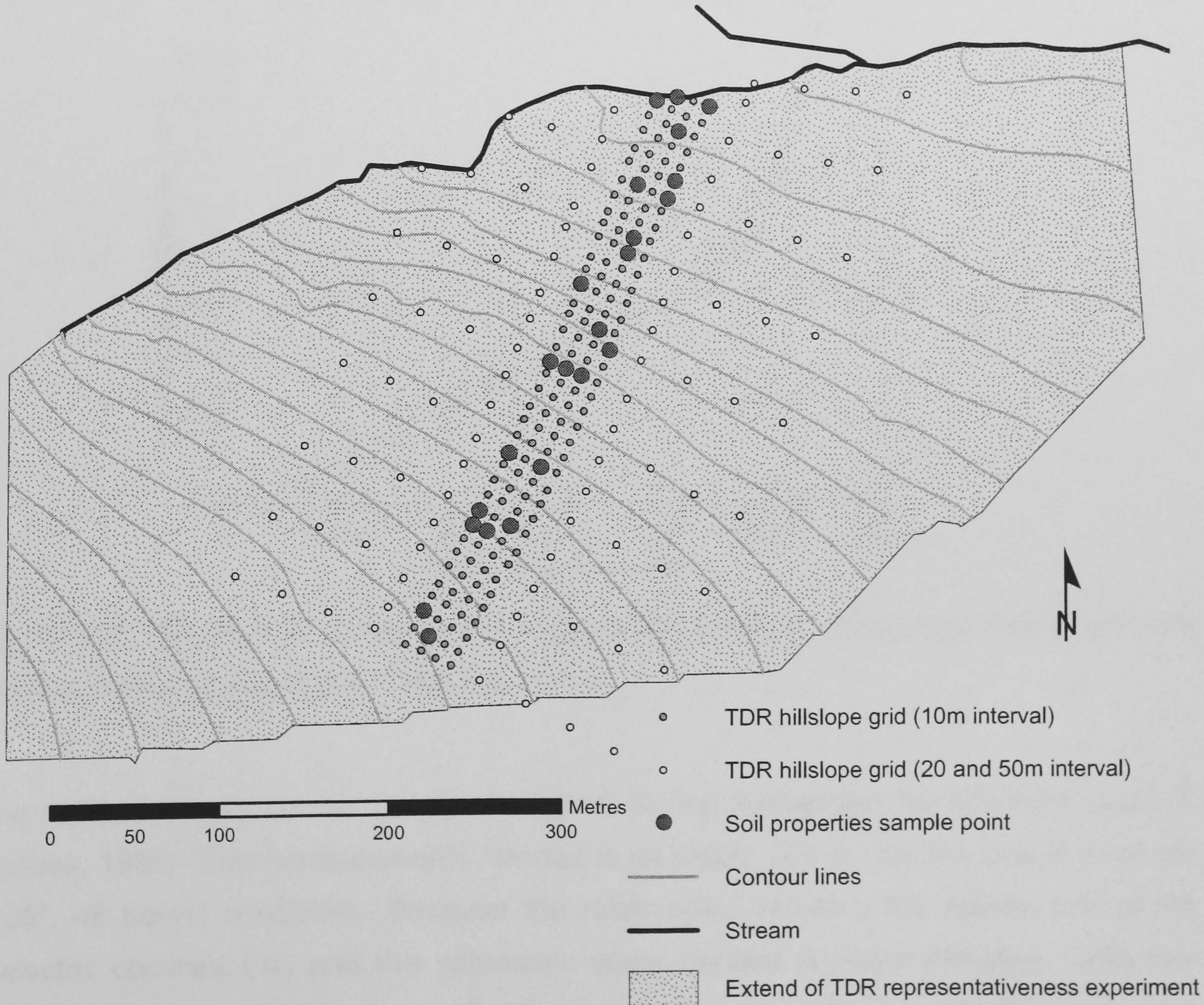


Figure 4.7: Layout of the TDR grid.

4.3.3 Thetaprobe calibration

ML1 and ML2 thetaprobes measure volumetric soil moisture content by Frequency Domain Reflectometry (FDR; Delta-T devices, 2000, pers. comm.). The main difference between FDR and TDR is the fact that FDR measures the reflection of a standing wave in the stainless steel wave-guides or rods. This means, that rods should be of a predefined length which cannot be adjusted (Delta-T devices, 2000, pers. comm.). The probe consists of a waterproof housing with four rods of 6 cm in length, which can be inserted into the soil. A signal is sent through the probe and produces a voltage standing wave in the wave-guides. The device is equipped with two generalised calibration curves, one for mineral and one for organic soils. The voltage, or the consequent soil moisture content, can be read off (Delta-T devices, 1996). Typical errors are ± 0.05 m^3 m^{-3} when using these calibrations, and ± 0.02 m^3 m^{-3} for a specific soil. Because of the non-linear curve between voltage output and soil water content (Figure 4.8), a soil specific calibration needed to be constructed. Therefore, and because in the experiments several thetaprobes were used (Section 4.3.4), all used thetaprobes were calibrated for Dartmoor soil samples in the laboratory.

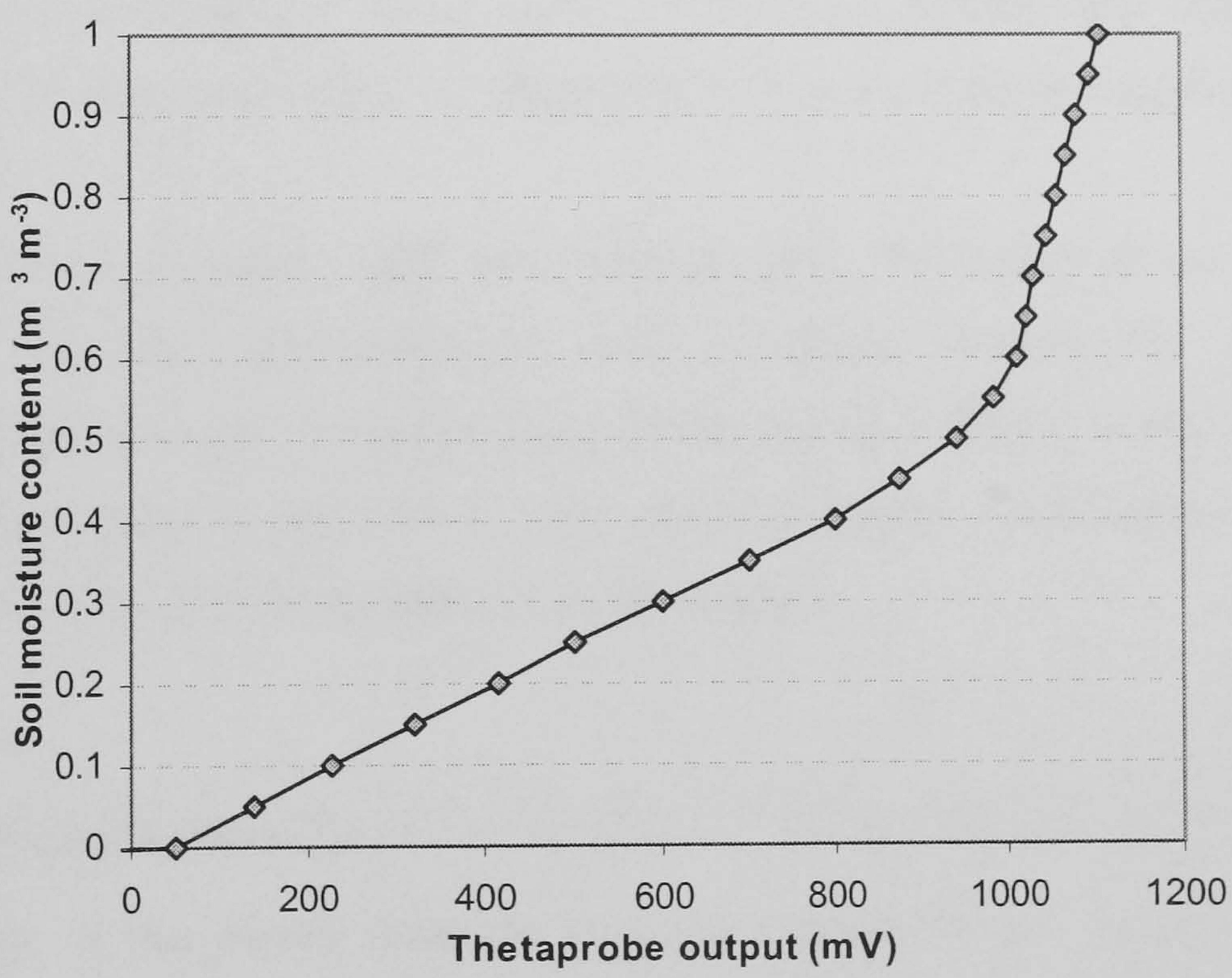


Figure 4.8: Generalised curve of the relationship between thetaprobe output and soil moisture content (After Delta-T devices, 1996).

The calibration was carried out as described by the thetaprobe manufacturer (Delta-T devices, 1996). Two measurements needed to be taken, one in wet and one in oven dry (105°, 48 hours) conditions. Because the relationship between the square root of the dielectric constant ($\sqrt{\varepsilon}$) and the volumetric water content is linear (Whalley, 1993 and 1994; White *et al.*, 1994), the calibration equation could then be calculated by using

Equation 4.10. The polynomial relationship between output voltage and water content is given by Equation 4.11, which should be used for wetter soils (Delta-T devices, 1996), such as on Dartmoor.

[4.10] $$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$

[4.11] $$\theta = \frac{(1 + 6.25V - 5.96V^2 + 4.39V^3) - a_0}{a_1}$$

where:
θ = volumetric soil moisture content ($cm^3\ cm^{-3}$);
V = output voltage (V);
a_0 = constant;
a_1 = constant.

Calibrations on the thetaprobes used in this study yielded specific values for a_0 and a_1, removing errors between thetaprobes. Therefore, systematic inconsistencies between thetaprobes in the field could be attributed to the method of measuring itself, and not the thetaprobes.

In a comparison between TDR and thetaprobes, Robinson *et al.* (1999) found that the thetaprobe slightly overestimates soil moisture values in comparison to TDR measurements, with an overestimation of the water content of 4% in comparison to TDR. This limitation has to be taken into account when comparing TDR and thetaprobe measurements described elsewhere in this thesis.

4.3.4 The representativity of the hillslope TDR grid to the entire hillslope

Soil moisture of the whole hillslope was measured on one occasion on a 10x10 m grid spacing to test the representativity of the TDR grid in relation to the entire hillslope. Measurements were carried out using thetaprobes (Delta-T devices, 1996). The total grid consisted of 1977 points, which were measured in a 7-hour period after nine days without rain during the wet season. Measurements were carried out line-wise in a north-south direction. Six pairs of people started at the top of the slope at 10 m intervals. Each individual group then walked transect-wise from the top of the slope to the bottom, measuring every 10 m (using a tape measure and a compass) covering a 60 m wide catena. Their exact locations at the start and end of each line were recorded with a GPS, and intermediate points were interpolated. This procedure was repeated until the hillslope was covered. Figure 4.9 shows the resulting grid layout.

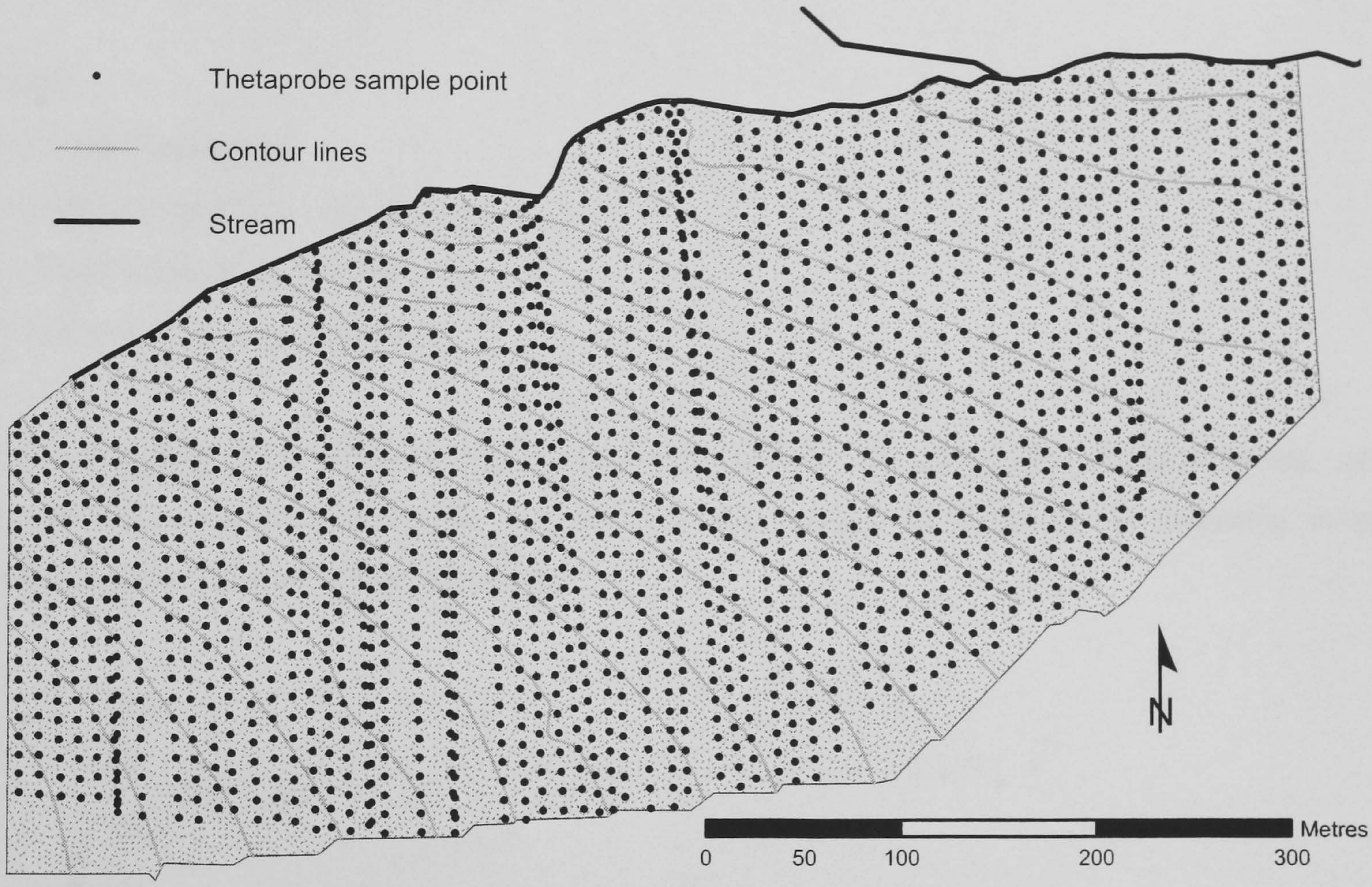


Figure 4.9: Layout of the TDR representativeness grid.

4.3.5 The TDR grazing grid

In order to estimate soil moisture values in an area with relatively high grazing pressures, a second TDR grid was installed, following the same layout as the hillslope TDR grid (Section 4.3.4 and Fig. 4.1). A suitable site was found on the eastern side of the existing grid, at which livestock was seen to be grazing often. The vegetation, very short grass, also suggested a high grazing pressure. Stocking densities were also monitored and compared to the existing grid and are described in Section 4.7.

4.3.6 Geostatistical interpolation

Large sets of spatial data can be analysed using geostatistics (Stein, 1997). The basis of geostatistical analysis is the fact that sample points close to each other are more likely to be spatially dependent than sample locations over a large distance. To get insight into the spatial dependence, the semivariance can be calculated (Van Soest, 1998), using Equation 4.12:

[4.12] $$\gamma(h) = \frac{1}{2N(h)} \sum_{1}^{N(h)} \left[z_h - z_{i+h} \right]^2$$

where:

$\gamma\ (h)$ = semivariance;

h = distance between sample pairs;

N = Total number of sample pairs;

z = value at the given location.

In the analysis, the semivariance is calculated for all possible pairs. Subsequently, all semivariance values are plotted against the corresponding distance h, resulting in a semivariogram (Fig. 4.10 for example).

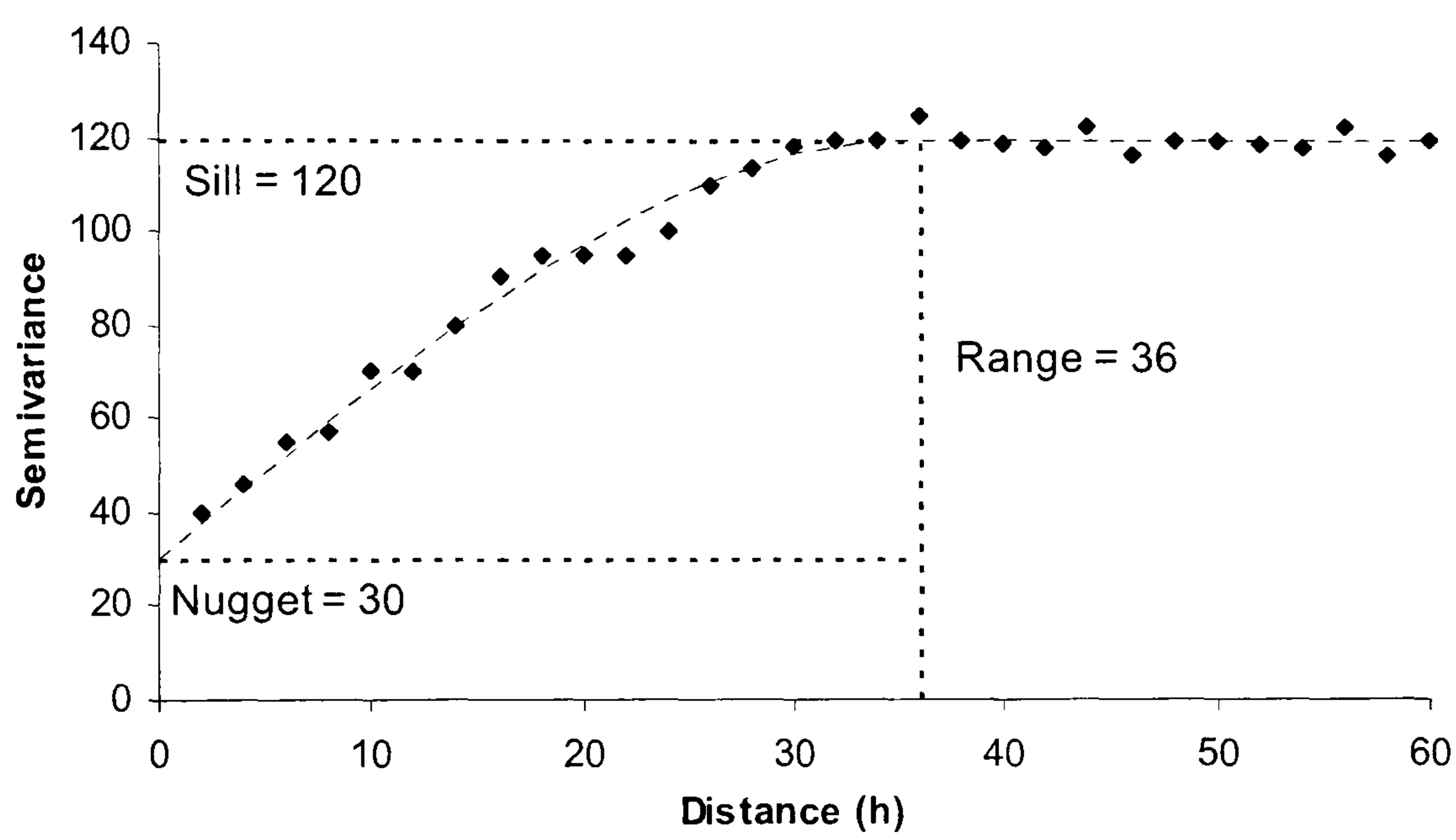


Figure 4.10: Example of a variogram (after Stein, 1993).

Three different parameters are estimated within a semivariogram: The nugget, sill and range. The nugget is the variation that cannot be explained by spatial dependence. The sill is the value of the semivariogram at the distance after which no spatial dependence exists between samples. The range is the measure within which variation is (partly) spatially dependent. The example semivariogram shown in Fig. 4.10 is theoretical and normally, a regression analysis needs to be carried out to estimate the best variogram.

This model can subsequently be used to spatially predict values at non-measured locations. This interpolation method is referred to as *kriging*, which can be regarded as a method of weighted averaging of a certain variable in a certain region (Webster and Oliver, 1990; Stein, 1993). For kriging, Equation 4.13 is used:

$$[4.13] \qquad \underline{t} = \sum_{i=1}^{n} \lambda_i \underline{y}_i$$

where:
t = optimal predictor;
λ = weight;
y_i = value at visited location x_i

The weight is assigned on the basis of the distance from a known value at a visited point to the predicted (unvisited) point and the semivariance at that distance. Using kriging on all points at point or cell basis within a certain grid, the variable can be mapped (Webster and Oliver, 1990). Within this study, kriging was used to interpolate soil moisture data across the hillslope. For a more detailed background on geostatistical analysis and kriging, further information can be obtained from Journel and Huijbregts (1978), Webster and Oliver (1990) and Cressie (1991).

4.4 Environmental variables in relation to soil moisture

Physical characteristics of the topsoil were determined at 23 TDR locations within the 10x10 m grid after TDR measurements were completed, so that soil moisture dynamics could be compared with the established soil parameters. Sites were selected to represent the different slope angles, vegetation and soil moisture conditions. The following soil parameters were determined: saturated hydraulic conductivity, organic matter content, water release characteristics, total porosity, the volume of transmission pores and bulk density. Texture was not determined because of the high organic matter content of the topsoil. The soil properties were obtained for the top 20 cm of the soil, in order to cover the length of the TDR rods. Soil profiles were described in terms of horizon nomenclature and horizon thickness, colour (Munsell), texture (Soil Survey, 1976), and soil series (Soil Survey, 1984). Figure 4.9 shows the points used for the soil properties analysis.
For the temporal analysis, the Antecedent Precipitation Index (API) was used to relate rainfall with soil moisture data. The background of this index is described in Section 4.4.5.

4.4.1 Vegetation cover and analysis

To compare soil moisture patterns with vegetation communities, on each hillslope TDR grid location of the permanent 10x10 m grid, vegetation descriptions were made in November 1998. A 50x50 cm quadrat was used with the TDR-rods situated in the centre of each quadrat, and percentage cover was estimated. The local slope was measured with a field clinometer. In total, 151 vegetation cover sample points were established.

At all 23 points of the TDR grid from which soil properties were analysed, vegetation cover estimates were carried out in August 1999. Baker and Lascano (1989) reported that in rods placed 500 mm apart, the sphere of influence at the topsoil was about 100 mm in diameter. However, this sphere was regarded as to be too small to carry out a reasonable vegetation description. A 20 x 20 cm quadrat was used because it was as close to the sphere of influence of the TDR-measurements as possible.

It was expected that single plant species did not necessarily show a direct relationship with soil properties and topography. It was also anticipated that vegetation communities were correlated with environmental variables. Therefore, vegetation species were analysed using TWINSPAN (Two-Way INdicator SPecies Analysis; Hill, 1979) in order to classify the vegetation into categories at different locations. TWINSPAN is a polythetic divisive method, which means that it divides quadrats into groups on the basis of all the species information. So the division is not based on the presence/absence of one species, but on the composition of the whole quadrat and is therefore regarded to be more quantitative. It is the most widely used polythetic divisive method for classifying vegetation groups (Kent and Coker, 1992). Although the exact details of the method are too complex to describe in this context, a short explanation will be given below.

The TWINSPAN classification is based on a dichotomy, a classification tree in which decisions are split into two, leaving one set of differential species on one end and second set at another end. The classification works in levels, in which each group is split into two groups, than the two groups are split into four, etc. The vegetation species are being split into so-called pseudo-species, which is a combination of the species and the percentage cover (Kent and Coker, 1992). In this study, pseudo species default cut-off values were used, with 0, 2, 5, 10, 20 and 100% vegetation cover, as suggested by Hill (1979).

For the classification, the first ordination or division is based on correspondence analysis. This method assigns arbitrary scores to each quadrat. In an iterative manner, a unique set of scores is produced for the quadrats and the species. These scores are used subsequently to give each species a value depending on the quadrat score in which it occurs. The species values generated in this way are then used to give new scores to the quadrats, depending on the species they contain. This is repeated iteratively until the scores remain the same, producing a primary ordination axis, both for the species and the quadrats along which they are ordered (Reid, 2001). For the first ordination in TWINSPAN, only the first axis ordination is used, and both groups are assigned negative or positive values. These values indicate to which group the quadrat is assigned. In the following ordinations, indicator species of the quadrats are assigned weightings in correspondence to a strong preference to a certain gradient. In the resulting classification, often one or more environmental gradients can be distinguished, using the occurrence and pseudo species as a reference (Kent and Coker, 1992).

4.4.2 Saturated hydraulic conductivity

Undisturbed samples for saturated hydraulic conductivity (K_{sat}) measurements were taken from 0-10 cm and 10-20 cm at each location with 10 cm diameter steel cores. Cores were driven into the soil using a hammer and a wooden log, excavated and wrapped in cling-film before being transported to the laboratory where they were stored at 4 °C before being analysed. The top and bottom of the core were trimmed flush and the core was left to saturate from the bottom upwards in a water bath to expel the air for at least 48 hours. Measurements were carried out using the falling head permeameter method (Klute & Dirksen, 1986). For each core, two triple measurements were carried out within a period of 48 hours.

4.4.3 Organic matter content

For the organic matter analysis, disturbed samples were taken from four depths (0-3, 4-7, 12-15 and 16-19 cm) at each location and stored at 4 °C in sealed polythene bags until analysis. Loss-on-ignition (l.o.i.) was used to determine the organic matter content. Sub-samples of around 4 g field-moist soil were placed in ceramic cups, oven dried at 105 °C for 24 hours and weighed. The cups were placed in a muffle furnace at 500 °C overnight until the black colour was removed and then re-weighed. Although at higher temperatures some clay minerals loose their structural water (Rowell, 1994), this was not regarded to be the case in the study area, as soils on Dartmoor have very high organic matter contents, and the mineral fraction mainly consists of sand and silt (Findlay *et al.*, 1984).

4.4.4 Water release characteristics, porosity and bulk density

Undisturbed cores (3 cm high, 5.4 cm diameter) for water release characteristics and bulk density were taken from four depths (0-3, 4-7, 12-15 and 16-19 cm) at each location. The same depths were used in order to be able to compare results with the organic matter contents (Section 4.4.3). The samples were wrapped in cling film and transported back to the laboratory, where they were stored at 4°C before analysis. The samples were trimmed flush and saturated. Water retention was established using a sand table with pressure heads at 0, -30, -50 and -100 cm (Klute, 1986; Rowell, 1994). This was assumed to be sufficient to reflect the naturally wet conditions in the study area. Samples were weighed every 24 hours to establish whether the cores were in equilibrium. Equilibrium was assumed when the difference between two measurements was less than 0.05 g (around 1%). The samples were then oven dried at 105 °C for 24 hours and weighed, to establish the dry bulk density. From the saturated and oven dry core results, the total porosity volume could be calculated (Rowell, 1994). Also, the volume of transmission pores in the samples was established, determined by the 0 to – 50 cm pressure head interval (Rowell, 1994). This variable was expected to be of main importance for the saturated hydraulic conductivity.

4.4.5 The Antecedent Precipitation Index

Rainfall data could be used to estimate the wetness state, using the antecedent precipitation index (API). The API on a given day is calculated from the sum of a series of precipitation values preceding that certain day, with a decay the longer the previous period (Weyman, 1975). The index can be calculated as:

[4.14] $$API_n = \sum_{t=0}^{n} P_t k^{-t}$$

where:
API_t = Antecedent Precipitation Index over n days;
P_t = precipitation at day t;
k = constant (-);

The constant k determines the decay over time. Within the catchment, due to limited data records, an optimum time period of 18 days (with a k of 0.9) was used, as a compromise between data limitations and the influence of rainfall over time.

4.5 Soil water pathways at the plot scale

In order to study the soil water pathways through the topsoil and subsoil, tensiometers were installed at three locations at the top, middle and bottom of the slope (location A, B and C, respectively, Figs. 4.1 and 4.11). The main aim was to monitor the pressure head response of the topsoil and subsoil through time during and after rain events.

4.5.1 Tensiometer installation

For this experiment, previously analysed soil sampling locations were used (Section 4.4), to be able to compare results to soil moisture conditions, topsoil properties, vegetation, and slope angle. A detailed soil description and classification was made at each location. At location A (Figure 4.1) tensiometers were installed at 10, 20, 30, 40, 60, 80 cm depth. At point B the same depths were used, with an additional tensiometer at 100 cm. At point C near the stream, tensiometers were only installed above the ironpan at 10, 20 and 30, because of saturated conditions close to the soil surface throughout the year.

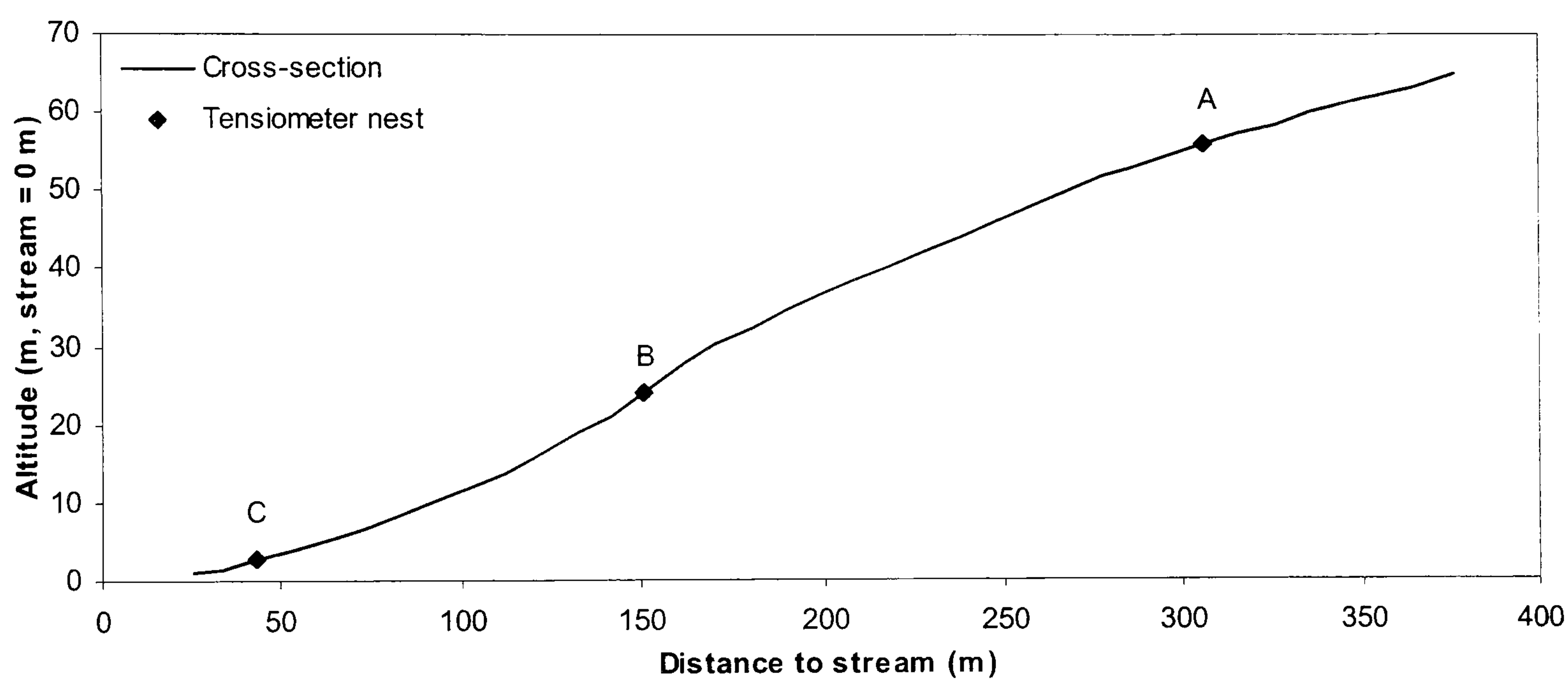


Figure 4.11: Cross-sectional profile of the hillslope with the tensiometer nests.

Porous cup tensiometers were used, connected with tubes to MicroSwitch pressure transducers at the soil surface. The pressure head was measured in one-minute intervals and logged on a 21x Campbell data logger at each site. Air temperature was also measured at each site, using the pre-calibrated temperature probe of the front of the data logger, in order to be able to compensate for temperature measured with the tensiometers and pressure transducers (Dowd and Williams, 1989).

4.5.2 Tensiometer and pressure transducer calibration

Pressure transducers were calibrated in the laboratory before installation. A tube was connected to the pressure transducer, in which a water column could be varied. The transducer output was measured using a Campbell 21X data logger and converted to pressure in cm H_2O. As the transducers were not temperature compensated, an attempt was made to establish the relation between temperature and pressure in the laboratory. However, temperature does not only affect the voltage output of the pressure transducers, but also has a real effect of the soil suction in the soil (Dowd and Williams, 1989). Therefore, this calibration was abandoned and temperature curves were plotted together with the soil suction graphs to facilitate manual comparison.

4.6 Digital GIS and Remote Sensing data at the catchment scale

4.6.1 Slope and topographic index calculations

Digital data on altitude (contour lines) and general topographic features (Scale 1:10,000) were available (Pecket, 1998, unpublished data). This was imported into a GIS (ArcInfo) and geo-referenced. With the aid of the digital contour lines, a digital elevation model (DEM) with a 7.5 m cell size was created. The DEM was used to calculate the different catchment boundaries and areas above the weir (headwater), the flume and for the entire catchment area. Although this delineation is relatively different due to the long convex hillslopes in the area, the GIS results were in good comparison with the boundary stones (Section 3.2.2).

The calculation method for establishing the DEM was designed specifically for hydrologically 'correct' digital elevation models, and uses stream information to force the water down. This means, that if during the calculations a sink (a cell which is surrounded by cells with a higher altitude and therefore no hydrological outlet (Burrough and McDonnell, 1992; Van der Meer, 1997) is established, this will automatically be filled up. In general, this is justified, as these features are very rarely observed in the field (ESRI, 1999). A more detailed description on the interpolation technique falls beyond the scope of this thesis.

With the aid of the DEM, slope angle calculations were carried out for each cell in the study area. Altitude values within the digital elevation grid are compared to the neighbouring cells, so each cell has 8 neighbours. The maximum downward gradient is then used to calculate the slope (Burrough and McDonnell, 1992).

The topographic index calculations, also based on the digital elevation model, can be described by Equation 4.15 (Kirkby, 1975; Quinn *et al.*, 1995):

[4.15] $$TI = \ln \frac{a}{\tan \beta}$$

where:

TI = topographic index (-);

a = upslope contributing area (per unit contour length);

$\tan \beta$ = local slope angle.

The index could be used to identify the likely locations and distribution of variable source areas in watersheds (Quinn *et al.*, 1995). It is based on the fact that catchment topography is an important factor in the spatial pattern of saturated areas (Section 2.6.2), and therefore for the localisation of flow routes. The computer programme GRIDATB (Beven, 1995) was adapted for grid sizes of more than 100 by 100 cells and then used to calculate the topographic index. Figure 4.12 shows the resulting altitude, slope and topographic index distributions within the catchment.

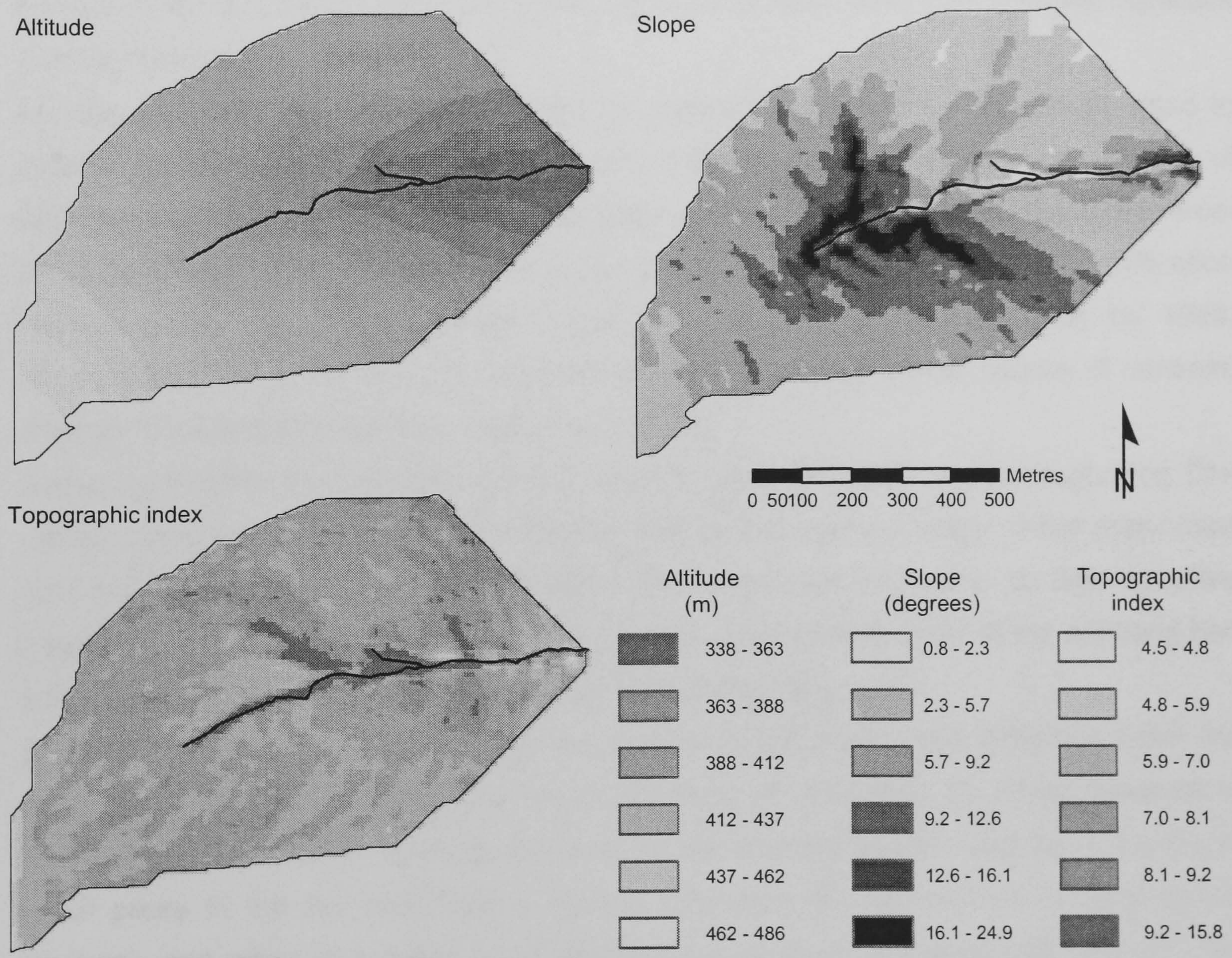


Figure 4.12: Altitude, slope and topographic index distributions in the study area.

4.6.2 The soil map

Hogan (1988) created a soil map of the catchment and surrounding area on a 1:25,000 scale (Section 3.6.2). This soil map was digitised and geo-referenced (Fig. 3.5). However, due to the small scale, it was mainly used as a reference, as it was not detailed enough to use it at the hillslope scale.

4.6.3 Air photo vegetation interpretation

Air photos from 1969, 1976 and 1992 were obtained from the Dartmoor National Park Authority (DNPA) and were geo-referenced in a GIS (ArcInfo). A vegetation map was created with the aid of the most recent air photo (1992; Fig. 4.11) and verified by field observations. The digital image consisted of multispectral data in the visible light only and was split into the three bands (red, green and blue). In each band, pixels had a digital number (DN) on a scale from 0 to 255, so in total each pixel had 3 digital numbers (Lillesand and Kiefer, 2000).

As different vegetation types reflect light in different wavelengths, this can be used to classify vegetation. The method used in this study was mainly based on knowledge of vegetation types obtained in the field and than compared to spatial patterns derived from the digital image. With the aid of the separate bands, a simple supervised classification was carried to identify four different vegetation communities (Richards and Jia, 1999; Lillesand and Kiefer, 2000). The red band especially showed a high degree of contrast, whereas the contrast in the blue band was very low.

Distinct vegetation communities in the area were used to identify the corresponding DN-values. Lillesand and Kiefer (2000) refer to this as the training stage of the supervised classification. Bracken was found to reflect no light in the red band, so was therefore distinctively different from other vegetation groups. Therefore, if pixels of the red band had a DN-value of zero, they could be classified as bracken (Fig. 4.13).

Similarly, the short grass areas within the catchment showed a high reflection within the red band, and if pixels of this band had a DN-value of more than 75, it was assigned to short grass. The heather classification was based on both the red and green bands, in which pixels in the red band had to have a DN-value of more than 0 (as opposed to bracken), and within the green band had to have a value of between 25 and 75. The remainder of the area was mainly taken up by grass and gorse (in the north) and was classified accordingly.

In the grazing pressure study (Section 4.7), distances from grazing livestock to certain vegetation types were calculated. In order to get a reasonable estimate of distances to the four different vegetation types, the scattered patterns of the vegetation map were simplified. The rationale behind this was that in reality, a single cell (resolution of 1.77 m, about 3 m^2 per cell) was unlikely to attract animals. In a GIS, a filter operation was used to remove single cells. A 3-cell radius (5.3 m) circular moving window was used to eliminate scattered, isolated cells. Within this window, the majority of vegetation classes was established and then assigned to all cells within this window.

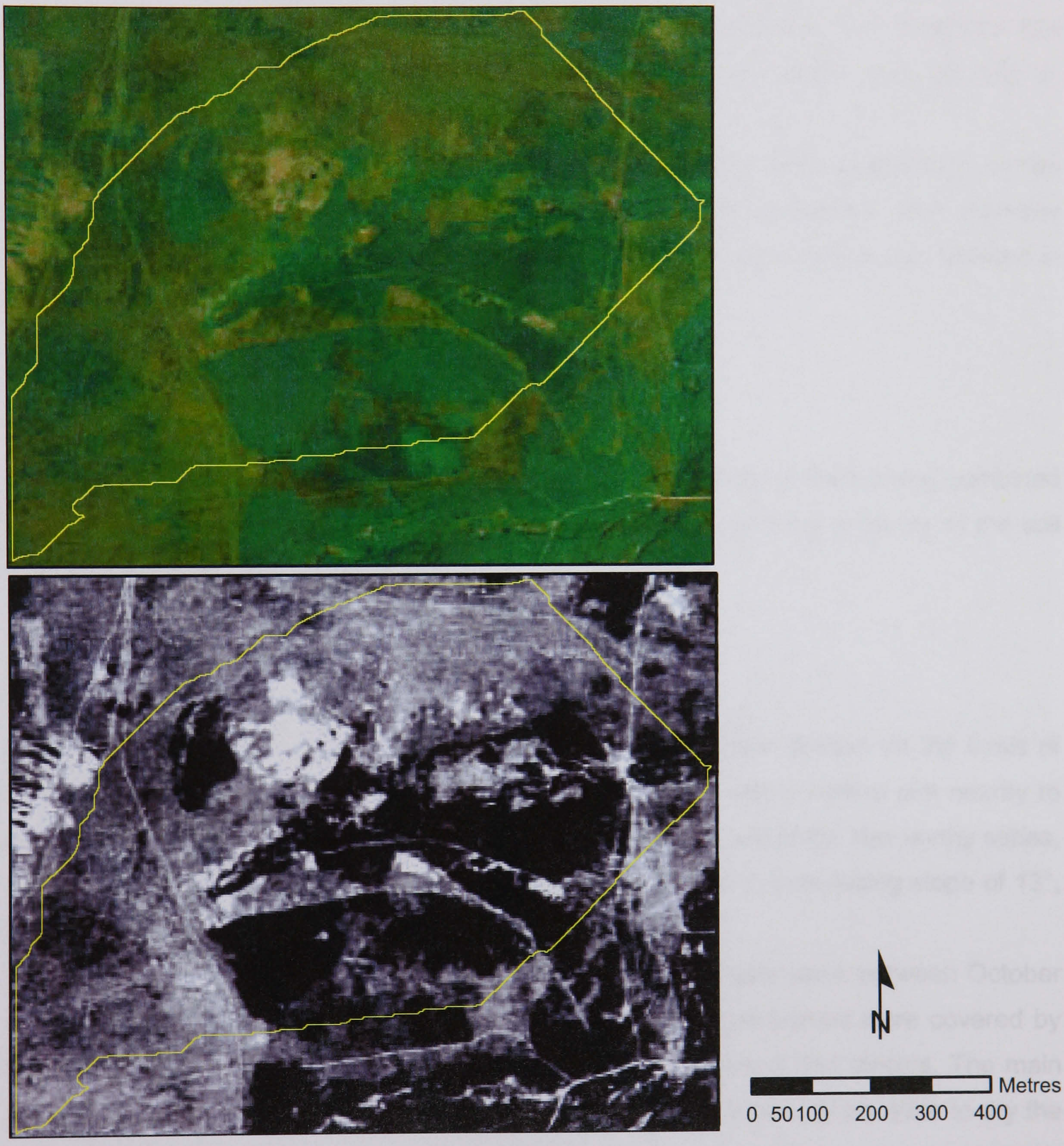


Figure 4.13: The 1992 air photo in full-colour (top) and the red band only (bottom). Note the clear cover of bracken (dark grey to black) and short grass areas (white).

4.7 Grazing pressure estimates

In the Holne Moor area on Dartmoor, data on grazing pressures and livestock distributions are not available. As the area is common land, livestock are allowed to roam. Therefore, it was necessary to estimate grazing pressures. In the summer of 1999, during each field visit, the locations of animals were indicated on a map. The weather conditions and the time were also noted. This exercise was carried out on 15 occasions. The resulting maps were digitised in a GIS (ArcView) and combined to produce a single map, yielding an overview of most intensively grazed and barely used zones.
With this method, several zones with a higher grazing density were established. In this area, another TDR grid (Section 4.3.5) was installed and monitored. Soil moisture dynamics and distribution were compared to the existing TDR-grid, which was situated in a relatively low-grazing pressure zone.

4.8 The burning experiment

The main aim of the burning experiment was to study the effects of the burning combined with vegetation, soil types, different fuel loads/fire intensities and the recovery of the soil through time.

4.8.1 Experimental set up

Two burning plots were established. The burning locations were chosen on the basis of the presence of heather. Each of those plots was combined with a control plot nearby to ensure comparable, unburned conditions. All plots were on a soil of the Hexworthy series, with an ironpan at around 50 cm depth. They were located at a north-facing slope of 13°, in a heather stand in the building phase, around 20 cm tall.
To ensure the opportunity of burning, which normally has to take place between October and the 15th of April (Thompson *et al.*, 1995c), the plots to be burned were covered by plastic sheets at approximately 40 cm height covering an area of 3x4 meters. The main aim was to keep the vegetation dry from rain, while ventilation was still possible to dry the vegetation and to minimise soil moisture depletion. They were installed a few weeks prior to the burn. Three days before the burn, the covers were removed. The burns were carried out on the 15th of March 1999, during a long dry spell of about two weeks (Plate 4.4). During the same week, farmers carried out several other burns across the moors, mostly in *Molinia* and/or gorse stands. Because of this difference in vegetation (*Calluna vs. Molinia* and gorse) the experimental burns were not fully comparable to the farmer's

prescribed swaling. Still, several burning and burned sites were visited and compared both visually as well as on the basis of soil moisture readings (Section 4.8.3).

The burn was initiated using gas torches and some dry *Molinia*. Weather conditions were ideal for prescribed burning, on a clear day with a weak easterly wind. The burn was carried out against the wind, to keep the fire under control, and fire beaters were used to extinguish the fire outside the plot.

Plate 4.4: The burning experiment.

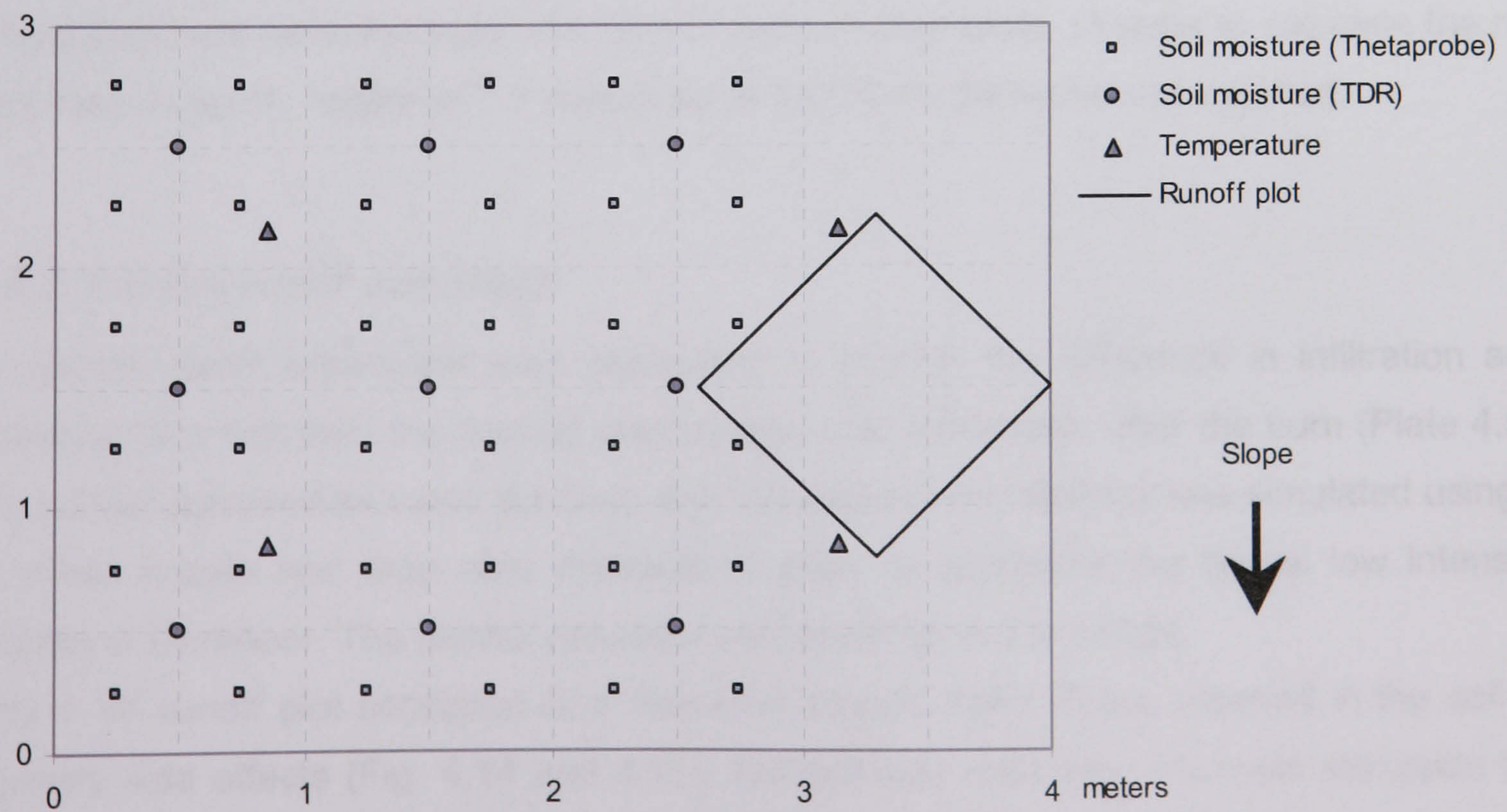


Figure 4.14: Measurement locations in the burning experiment.

Temperature in the soil during a burn was anticipated to decrease sharply with depth, so the influence of the fire is very shallow (Section 2.8.3). Therefore, soil temperature was measured only in the uppermost part of the soil. Temperatures before, during and after the burn were measured using 10 thermistors and a Campbell 21X data logger on one plot only. The set up was assembled and calibrated in the laboratory beforehand. The thermistors were installed at four locations. At each location one was installed at the soil surface (0 cm), one at 1 cm depth, and on two of the four locations, a third one was installed at 3 cm depth. Measurements were taken at 10-second intervals throughout the course of the burn.

The plot was divided into two sections: one plot of 3x3 m for the undisturbed monitoring of soil moisture and temperature, and a 1x3 m strip was left on the side for the rainfall and runoff experiments (Fig. 4.14). The soil moisture plot was divided into 50x50 cm cells (totalling 9 m^2), covering 36 cells per burning plot. In each of the cells, moisture of the top six cm of the soil was measured using a thetaprobe (Section 4.3.3). Additionally, TDR-rods were installed vertically at 0-20 cm depth at 1 m intervals at 9 locations (Fig. 4.12). Directly before and after the burn, soil moisture was measured. Measurements were also carried out approximately two months after the burn, and then at time steps depending on weather and soil moisture status. The same procedure was used for the control plot. Water repellency was measured directly after the burn on the topsoil, using the Water Drop Penetration Time Test (WDPT-test) at a few randomly selected points (Ritsema, 1994; Doerr, 1998)

By removing, drying and weighing the (remaining) vegetation, fuel loads on the plots were estimated. Each of these plots was divided into four equal area plots of 0.25 m^2 each. Vegetation was removed from one control and two burn plots, in order to calculate the net fuel load, in kg dry matter m^{-2}. It was dried at 105 °C for 24 hours and weighed.

4.8.2 Rainfall runoff simulation

A rainfall runoff experiment was conducted to monitor the difference in infiltration and overland flow between the burned and control plots a few days after the burn (Plate 4.5). No rainfall occurred between the burn and this experiment. Rainfall was simulated using a smallest nozzle and drop size available in order to represent the typical low intensity rainfall of Dartmoor. The rainfall simulator was installed at 2 m height.

The 1 m^2 runoff plot consisted of a diamond shaped metal frame, inserted in the soil to prevent side effects (Fig. 4.14 and 4.15). Rainfall was collected in funnels alongside the plot to monitor the distribution and intensity of the rainfall. Two TDR rod pairs were installed in the middle axis of the plot, to monitor change in soil moisture over the top 20 cm of the soil, and measurements of the top 6 cm were carried out alongside the plot with a thetaprobe to prevent disturbance. A funnel was installed under the outlet of the plot to collect the overland flow. During the experiment, which lasted one hour, the rainfall was switched off during one minute every ten minutes, to allow recording of soil moisture and rainfall.

Plate 4.5: Rainfall-runoff plot set-up.

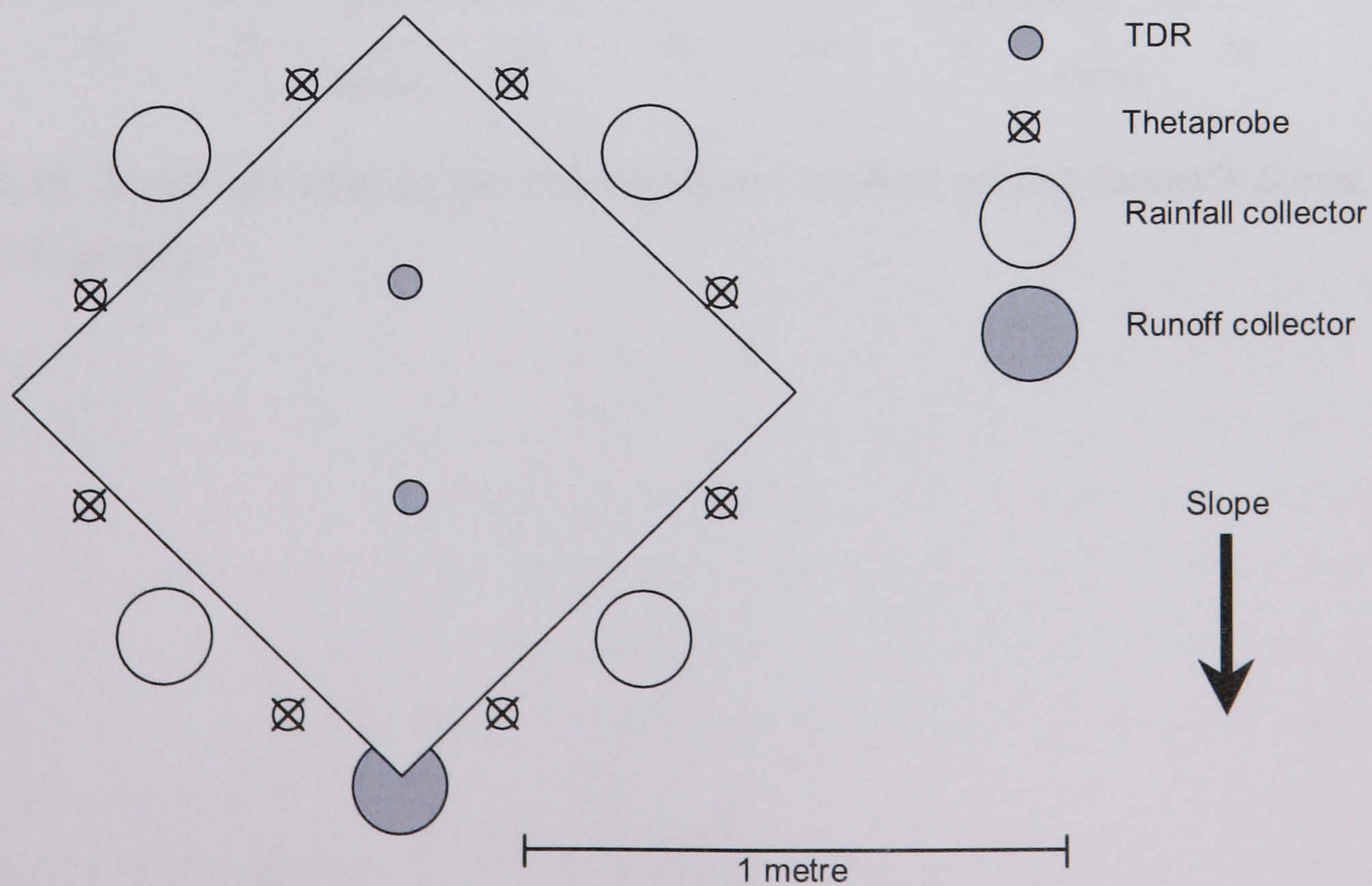


Figure 4.15: Set-up of the rainfall-runoff simulation.

4.8.3 Soil moisture patterns under farmer's burns

On the 18th March 1999, 3 days after the experimental burns in the catchment area, farmers carried out a burn both on the west of the study area, as well as on the east of Venford Reservoir (Figure 3.8). In order to compare results of the burning experiment in the study area with burns carried out by local farmers, several soil moisture transects were carried out two hours after the burn following the layout as shown in Fig. 4.16. Readings were taken inside and just outside the burned areas, using a thetaprobe. Both transects were on the east of Venford Reservoir on the same slope facing the north west, with a gradient of approximately 10°. The vegetation in the area was a combination of gorse, bracken and *Molinia*, but no *Calluna* was present.

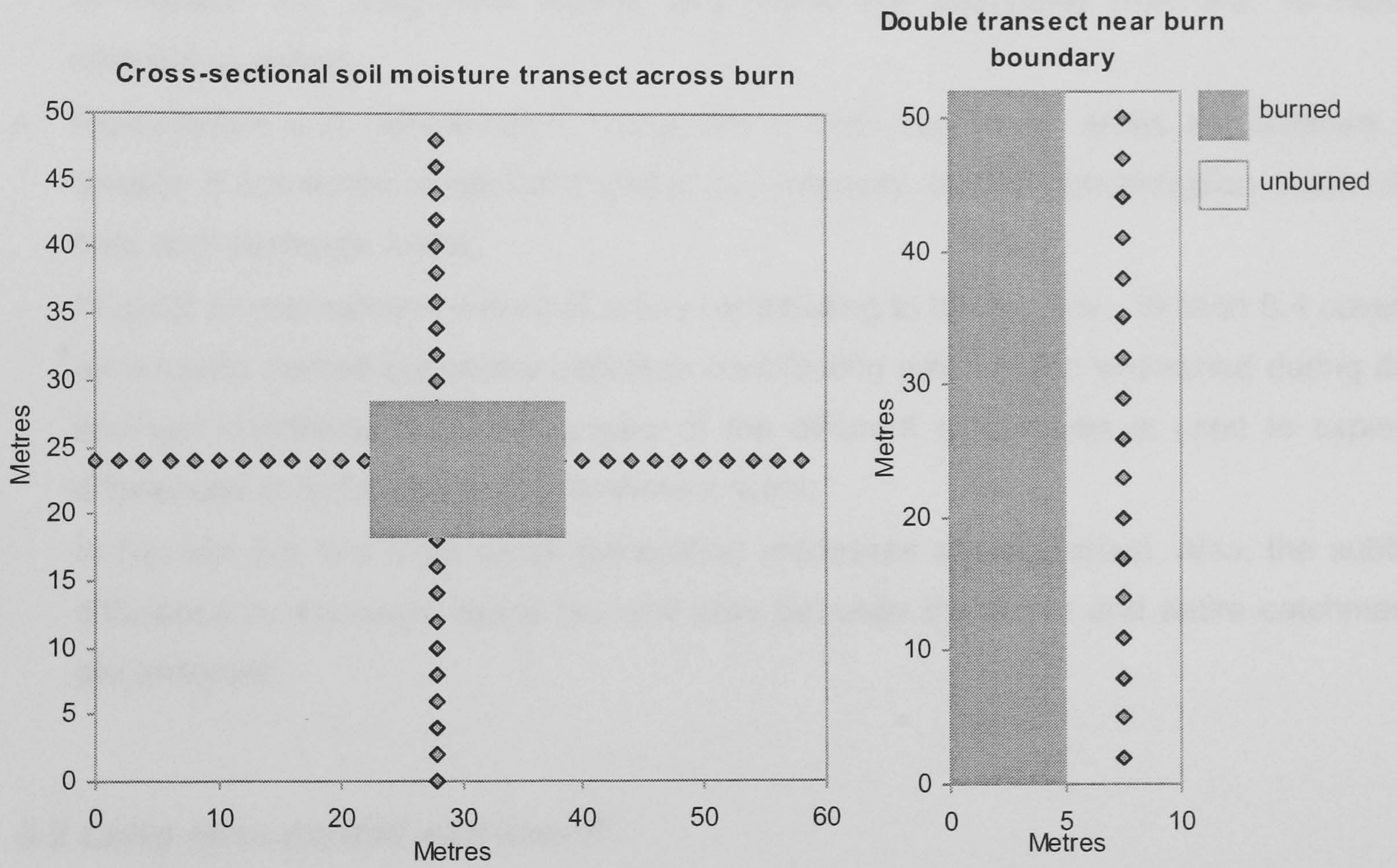


Figure 4.16: Schematic view of the soil moisture transects across farmer's burns, east of Venford Reservoir.

Chapter 5: Catchment hydrology

5.1 Introduction

This chapter describes the hydrology of the headwater catchment and the catchment as a whole. The aim is to get an insight into the processes that determine the response to rainfall at the catchment and sub-catchment scales (Chapter 1) and to provide a context for the hillslope study (Chapter 6). With the aid of the rainfall-runoff response, the possible water pathways on the hillslope are distinguished. These pathways will subsequently be investigated in a more detailed study in Chapter 6.

- In Section 5.2, long term rainfall and runoff are described over the 19-month measuring period;
- Precipitation and rainfall-runoff responses of both catchment areas are outlined in Section 5.3 in terms of rainfall amounts and intensity, time of concentration, response time and discharge levels;
- In order to estimate the extent of areas contributing to stream flow, Section 5.4 covers an analysis carried out on the minimum contributing areas of the watershed during dry and wet conditions. The topography of the different catchments is used to explain differences in hydrology at the catchment scale;
- In Section 5.5, the main runoff generating processes are discussed. Also, the subtle difference in discharge levels per unit area between the upper and entire catchment are analysed.

5.2 Long term rainfall and runoff

5.2.1 Rainfall distributions and measurement representativity

For the analyses of rainfall amounts and distribution, the 1999 data set was used. Precipitation was measured at one location only within the catchment (340 m). From two other locations outside the study area, rain data were available (Section 4.2 and Fig. 4.4). The latter gauges showed that 1999 was a wetter year than the long-term average (2022 mm at the Venford gauge), around 350 mm higher than on average (Environment Agency, 2000, unpublished data). It was expected that this relatively wet year did not have large effects on the results of this study, as the patterns of individual storms are unlikely to be different between years.

Daily records of the Venford Reservoir gauge and the study area were compared and it was shown that, despite some missing data, rainfall amounts were similar. All major discrepancies between the gauges could be related to known mechanical problems during the recording period in the study area. Periods of incomplete data at the study site were also discarded from the Venford gauge in order to assess the influence of topography on rainfall amount. Figure 5.1 shows the (not adjusted) monthly rainfall of 1999 of the three gauges. The adjusted annual rainfall for the catchment gauge for 1999 was about 100 mm more than at the reservoir, suggesting an increase in rainfall with altitude.

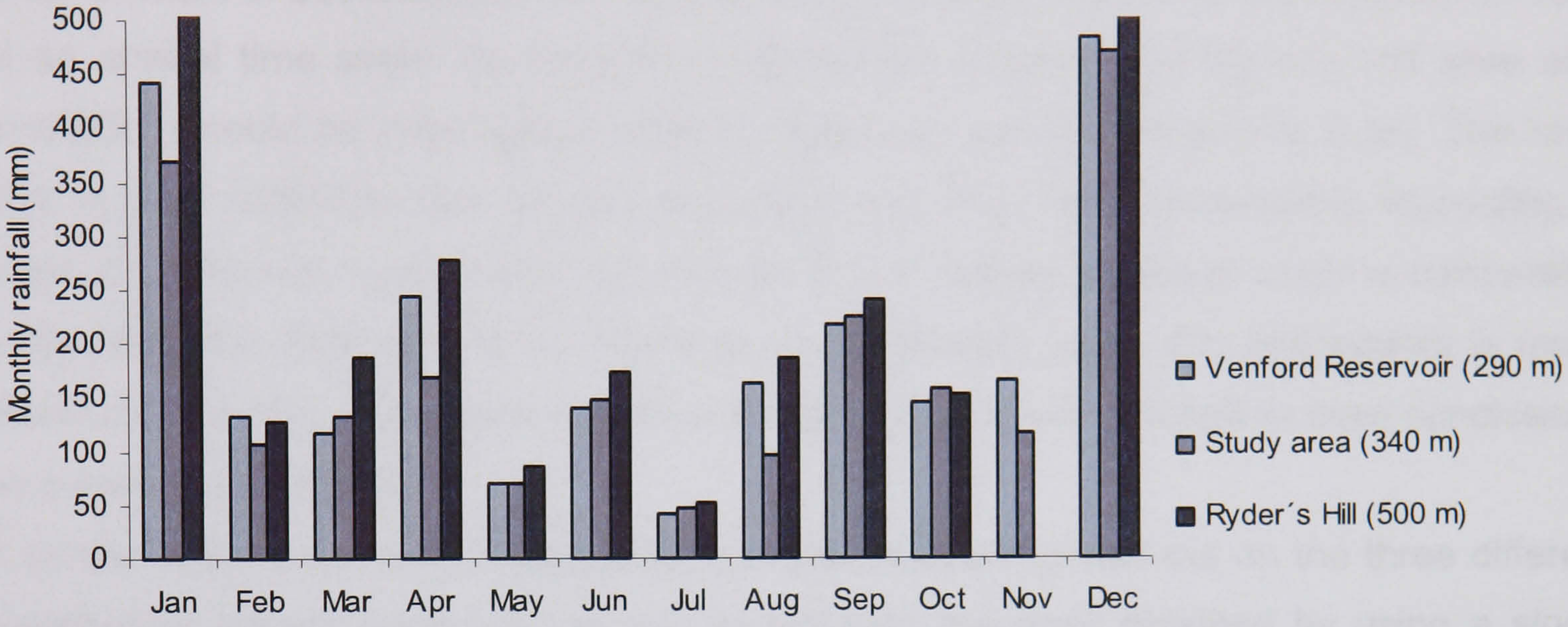


Figure 5.1: Monthly rainfall figures for 1999 for the rain gauges at Venford Reservoir, the study area, and Ryder's Hill.

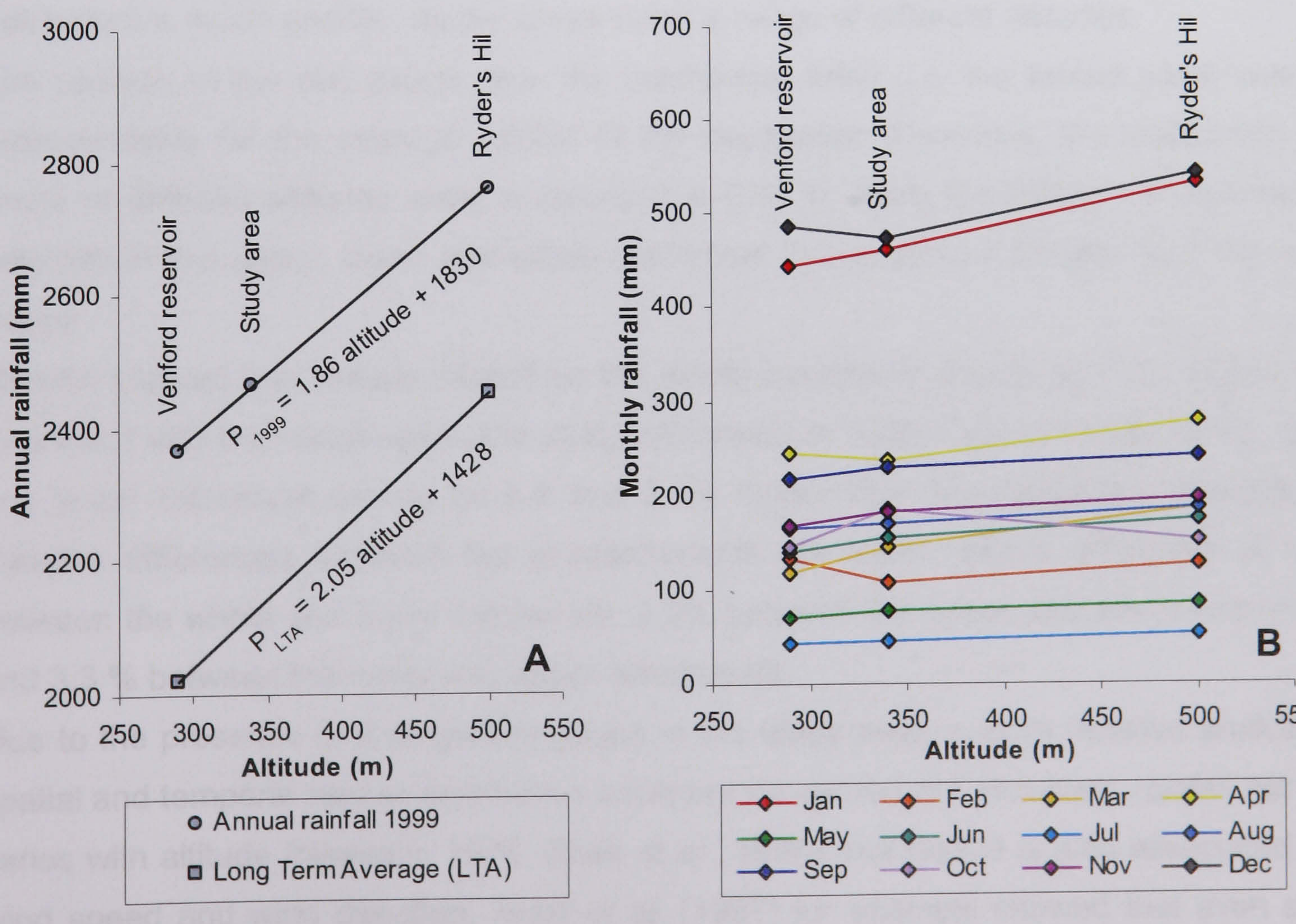


Figure 5.2: Annual (a) and monthly rainfall (b) vs. altitude for 1999.

Based on the three rain gauges, a simple linear regression between the altitude and the annual rainfall for 1999 was carried out to estimate the altitude effect (Fig. 5.2). All three gauges were situated on a hillslope with a north to northeastern aspect.

The regression model shows an increase of 186 mm per 100 m altitude increase, equal to 7% per 100 m, much lower than for the Plynlimon catchment in Wales, studied by Newson (1976) and Chappell (1990). Although the R^2-value (0.999) has a limited validity due to the small amount of observations (n = 3), it is clear that the relationship was relevant in 1999 at an annual time scale. As long-term data for the Venford and Ryder's Hill were also available, it could be investigated whether 1999 was representative (Fig. 5.2a). The long-term annual rainfall for the gauges was 2022 and 2452 mm, respectively. According to these data, rainfall increases by 205 mm per 100 m altitude increase, which is comparable to the data for 1999 (186 mm). However, on a monthly basis, this relationship is much more variable (Fig. 5.2b), and data from a single year is not sufficient to draw conclusions on a monthly timescale.

A simple adjustment for the annual time scale could be carried out on the three different catchments (upper, lower and whole) to estimate the error obtained by using a single raingauge in the study area. The difference in precipitation between the highest and lowest point in the catchment area is relatively large (2510 and 2733 mm for 1999 respectively, based on 186 mm 100 m^{-1}). However, the difference in rainfall per (sub) catchment is much smaller, as the areas cover a range of different altitudes.

The position of the rain gauge near the catchment outlet (*i.e.* the lowest point) was not representative for the average rainfall of the catchment. Therefore, the distribution and areas of different altitudes were analysed in a GIS, to study the different annual rainfall amounts in the upper, lower and entire catchment in comparison to data from the study gauge.

Results showed that annual rainfall for the whole catchment should be 4.2% higher than measured with the raingauge in the study catchment in 1999. Typical values for the upper and lower catchment should be 6.9 and 3.4% higher than the raingauge, respectively. Relative differences between the subcatchments are lower, with a difference of 0.7% between the whole and lower catchment, 2.5% between the upper and whole catchment, and 3.3 % between the lower and upper watersheds.

Due to the presence of a single raingauge in the study area, a more detailed analysis of spatial and temporal rainfall distribution could not be carried out. However, rainfall not only varies with altitude (Newson, 1976; Shah *et al.*, 1996), but rainfall is also associated with wind speed and wind direction. Arazi *et al.* (1997) for example showed that even small scale topographic inhomogeneities (catchment and hill slopes with an altitude difference of a couple of tens of metres) have an effect on precipitation, both on the inhomogeneity itself as well as the area downwind of it. Wood *et al.* (1988) described that, especially in relatively small catchments, runoff generation becomes more sensitive to rainfall recordings at individual rain gauges, indicating the importance of representative position of the gauge.

It could be concluded therefore, that the distribution of rainfall is not evenly distributed in the study area. The upper catchment receives more rainfall than the lower catchment, an effect that has to be taken into account in the water balance calculations in this chapter. However, it is only possible to calculate the relation rainfall-altitude on a yearly basis. On a shorter time scale the variability is greater. Also, no estimates of the relationship between rainfall and wind effects were possible. It was therefore decided not to adjust rainfall figures in calculations for these effects. Although errors are only minor, they should not be omitted, but be used on a more qualitative basis instead.

5.2.2 Rainfall statistics

The wettest period occurred in winter, with maximum monthly rainfall of 396 mm in January 1999 and 473 mm in December 1999. Least rainfall was recorded during summer in July 1999 with 24 mm. The maximum rainfall amount recorded during one day was 90 mm (19 January 1999) as part of a rainstorm lasting 28 hours.

5.2.3 Streamflow

The recording periods for streamflow at the entire watershed and the headwater catchment scales did not fully coincide (Fig. 5.3), so statistics were calculated for different periods, avoiding time periods with incomplete records (Table 5.1). Averages were calculated based on the 15-minute recording interval. When data were missing for a short period, data from the matching data set was also removed to facilitate comparison.

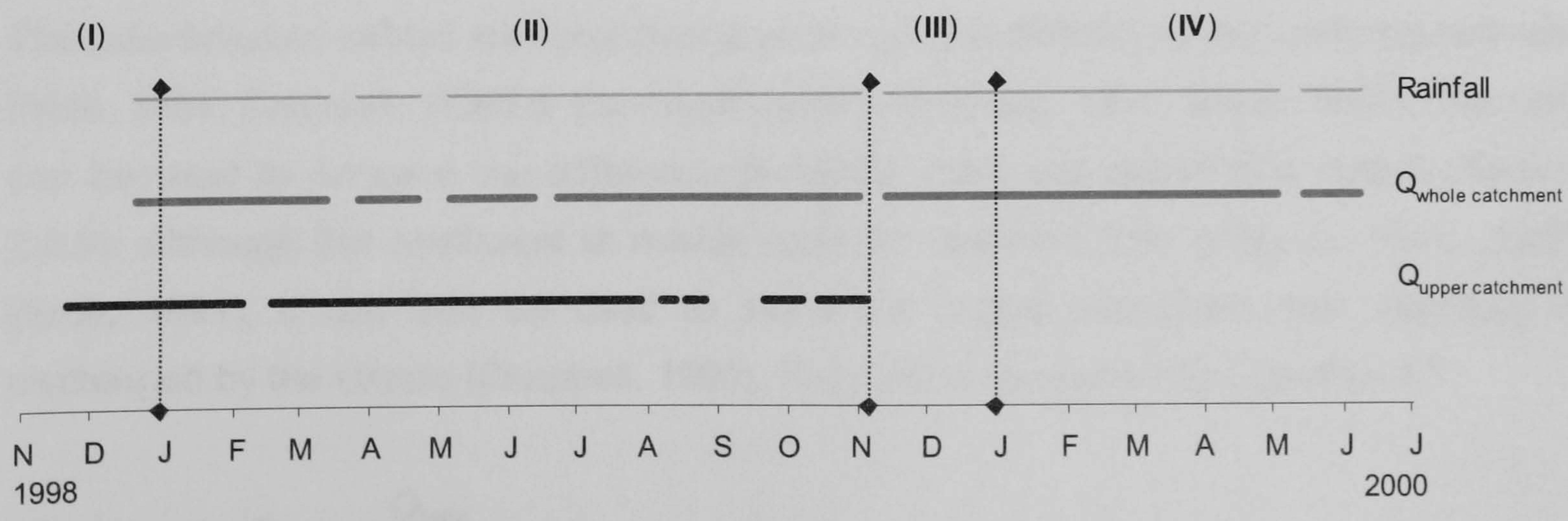


Figure 5.3: Recording periods for the upper and lower catchments, including rainfall.

Winter average streamflow (October through March) was 0.43 mm hr^{-1} at the catchment outlet and 0.37 mm hr^{-1} for the headwater catchment (Table 5.1). On average in winter the discharge per unit area in the whole catchment was therefore about 14% larger than in the upper catchment. However, in summer the difference in average streamflow between both the (sub) catchments was negligible, with 0.113 mm hr^{-1} for the whole catchment and 0.114 mm hr^{-1} for the headwater catchment.

During the summer period in 1999, the discharge measured at the headwater catchment decreased to virtually zero around August 20th, in comparison to discharge of 0.018 mm hr^{-1} at the whole catchment. Rainfall in the four weeks prior was less than 70 mm, with only 3.5 mm in the 12 days before the discharge ceased at the headwater catchment. Low flows such as this could indicate limited storage space in the catchment, as virtually all of the rainwater is removed from the watershed. Although discharge in the stream was limited, the volume of hyporpheic flow (groundwater flow underneath weir or flume) is unknown and is likely to still contribute to the discharge of the entire catchment.

Table 5.1: Average discharge levels and amounts in different recording periods.

Period		Headwater catchment		Whole catchment		Q_{whole} / Q_{upper}
		Q_{mean}	Q_{mean}	Q_{mean}	Q_{mean}	
		(l s^{-1})	(mm h^{-1})	(l s^{-1})	(mm h^{-1})	(-)
Ia	20/11/98 - 20/12/98	6.0	0.177	*n/a*	*n/a*	*n/a*
Ib	21/12/98 - 31/1/99	21.8	0.646	124.2	0.732	1.13
IIa	1/1/99 - 31/3/99	12.4	0.368	75.4	0.444	1.21
IIb	1/4/99 - 30/9/99	3.9	0.114	19.1	0.113	0.99
IIc	1/10/99 - 4/11/99	7.9	0.233	41.4	0.244	1.05
III	5/11/99 - 31/12/99	*n/a*	*n/a*	87.1	0.513	*n/a*
IV	1/1/00 - 8/6/00	*n/a*	*n/a*	40.0	0.236	*n/a*
Summer	1/4/99 - 30/9/99	3.9	0.114	19.1	0.113	0.99
Winter	20/12/98 - 31/3/99 and 1/10/99 - 4/11/99	12.3	0.366	72.2	0.426	1.17

5.2.4 Rainfall-runoff ratio definition

The ratio between rainfall and total discharge or runoff is defined as the rainfall-runoff ratio (Hino, 1987; Chappell, 1990) or the runoff coefficient (Black, 1991; Shaw, 1994). This ratio can be used to compare the difference in rainfall input and streamflow output (Section 2.6.5). Although the coefficient is mainly used for overland flow analyses (Hino, 1987; Black, 1991), it can also be used to study the rainfall proportion that ultimately is discharged by the stream (Chappell, 1990). The ratio is calculated by Equation 5.1:

[5.1] $$C_{runoff} = \frac{Q_{total}}{P_{total}}$$

where:

C_{runoff} = Runoff coefficient (mm mm^{-1});

Q_{total} = Total amount of runoff (including baseflow) (mm);

P_{total} = Total amount of rainfall within the same time period (mm).

The main advantage of this ratio over the runoff percentage (which uses the volume of storm runoff instead of the total runoff, Section 5.4.2) is that no assumption is needed for the separation between peak flow and baseflow. Also, the ratio can be used more easily on long-term rainfall-runoff response analysis in order to establish an estimate of the balance between the input and output of the catchment system. A disadvantage is that the distinction between short term (rainfall) and long term processes is less clear.

The difference between the two usages is that in the case of overland flow analyses, this ratio cannot be higher than 1.0, because the output cannot be larger than the input. However, in catchment studies, especially in long-term analyses, values can reach higher values due to wet antecedent moisture conditions, groundwater discharge, low evapo-transpiration rates and little precipitation during certain periods (Chappell, 1990).

5.2.5 Long-term rainfall-runoff ratios

For the whole catchment, monthly rainfall-runoff ratios were 1.18 in January and 0.73 in September. Chappell (1990) showed comparable rainfall-runoff ratios between 0.42 and 1.32 under grass in the Tir Gwyn catchment in Wales, with high values attributed to low evapo-transpiration rates. Unfortunately, values for the headwater catchment could not be obtained due to some missing records for most months. Therefore, specific periods were chosen to compare rainfall-runoff ratios between catchments (Section 5.2.3). A disadvantage was that ratios between different periods were more difficult to interpret, as the periods were of different length.

During winter, runoff coefficients were regularly close to 1.0 (Table 5.2), decreasing through time when progressing into summer. This indicates, that a higher percentage of the rainfall is leaving the watershed as runoff than in summer. This might partly be due to reduced evaporation and transpiration rates and lower interception capacities throughout the winter (Newson, 1976). Also, in autumn, water is stored in the soil, reducing the potential storage space, causing a higher runoff.

Table 5.2 shows a tendency of higher rainfall-runoff ratios in the whole catchment than in the upper catchment. Additionally, the difference in ratios between both (sub) catchments appears to be more profound in winter than in summer. In the period between the 1st and the 21st of January, typical for the winter period, the ratio for the whole catchment was 1.25 and 0.88 for the headwater catchment. In summer, in the period between the 22nd of June and the 28th of July, these values were 0.40 and 0.30, respectively.

The ratios are adjusted for increased rainfall with increased altitude (Section 5.2.1). Therefore, it could be concluded that the difference in outflow volumes per unit area between catchments, also shown in Section 5.2.3, is evident as well from the average long-term rainfall-runoff ratios.

Table 5.2: Long term rainfall-runoff ratios for the whole and headwater catchment. For the ratio calculations, total rainfall was adjusted for altitude (Section 5.2.1).

Period (1999)	Time (days)	P_{gauge} (mm)	$P_{adj, whole}$ (mm)	$P_{adj,upper}$ (mm)	Q_{whole} (mm)	Q_{upper} (mm)	$C_{runoff, whole}$	$C_{runoff, upper}$	Remarks
1/1-21/1	20	321.4	334.3	343.6	416.9	301.8	1.25	0.88	
25/1-4/2	10	14.4	15.0	15.4	62.5	58.3	4.17	3.78	Short measuring period with wet antecedent conditions and little rainfall
17/2-13/3	24	158.8	165.2	169.8	137.7	147.1	0.83	0.87	
27/3-22/4	26	223.2	232.1	238.6	125.4	125.1	0.54	0.52	
6/5-21/5	15	35.4	36.8	37.8	27.6	19.8	0.75	0.52	
24/5-11/6	18	144.8	150.6	154.8	66.6	81.0	0.44	0.52	
22/6-28/7	36	75.4	78.4	80.6	31.5	24.5	0.40	0.30	
7/8-12/8	5	44.4	46.2	47.5	3.2	0.5	0.07	0.01	Headwater catchment outlet nearly dry
17/8-26/8	9	27.6	28.7	29.5	12.6	2.7	0.44	0.09	Headwater catchment outlet partly dry
20/9-7/10	17	147.6	153.5	157.8	95.3	111.1	0.62	0.70	

5.2.6 The flow duration curve

A flow duration curve shows the percentage of time during which a specified flow rate is equalled or exceeded (Weyman, 1975; Black, 1991). Such a curve can be used to analyse the consistency or variability of the streamflow. Although the time period of the data set was limited, it was expected that the flow duration curves for the upper and whole catchment could provide useful information about the variability of the stream and the difference between the flow at both weirs.

In the flow duration curves of both subcatchments (Fig. 5.4a & b) the discharge axis is plotted on a logarithmic scale to enable more precise comparison at low flows (Gregory and Walling, 1973). The flow duration curves for the study catchment show that discharge levels seldom exceed 0.59 mm hr^{-1} (in 6% of the time) and have a steep rise above this level compared to lower discharge levels. In the catchment, high discharge levels are an order of magnitude higher than the winter and summer average levels.

In order to compare the flow duration curves of the headwater catchment and the whole catchment, discharge levels are expressed in mm hr^{-1}. Close examination yielded a very close similarity between the two (Fig. 5.4c). The figure shows that there are some minor differences between the whole and upper catchment. The variability could be compared using the 30:70 ratio, which is the discharge at 30% of the time divided by the discharge equalled or exceeded in 70% of the time. The higher this ratio, the more variable the streamflow (Gregory and Walling, 1973). Occasionally, a 10:90 ratio is also used. For both subcatchments, the 30:70 ratio was around 4.0, whereas the 10:90 ratio was about 15.5. Because of the close visual similarity and the similarity between both ratios, it was suggested that the runoff processes in each catchment were similar. Only at the most extreme discharge levels (streamflow equal or exceeded in 2% of the time), the whole catchment appears to be discharging more water per unit area than the upper catchment.

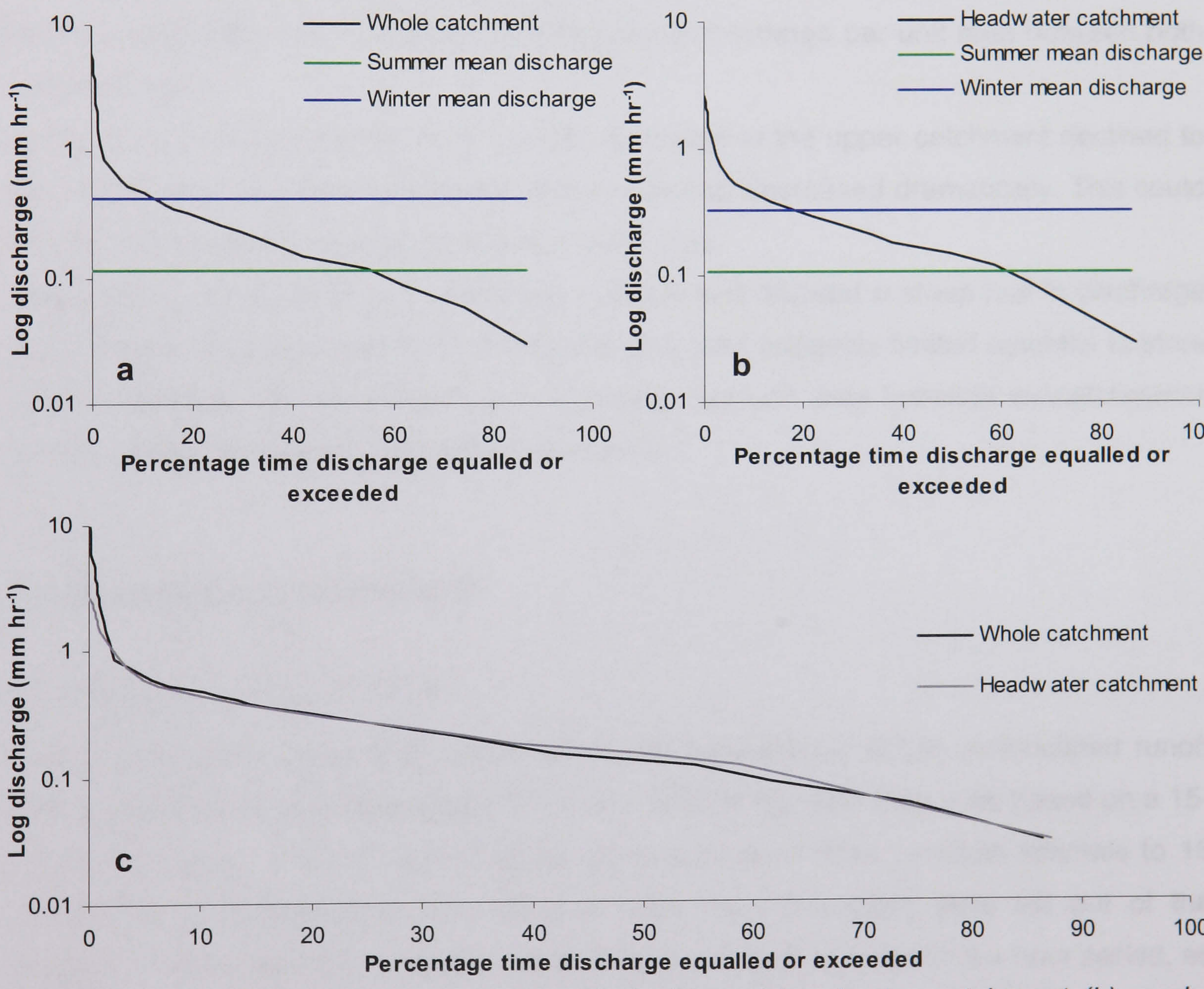


Figure 5.4: Flow duration curves of the whole (a) and headwater catchment (b), and a comparison between the two (c).

In the study area, rainfall intensities and amounts are generally relatively low. The steep flow duration curves, suggest a very flashy stream. If the stream responds quickly to rainfall, it is suggested that a relatively small proportion is stored in the soil. The shape of the duration curve could therefore be an indication of a low storage capacity in the catchment (Weyman, 1975).

5.2.7 Summary

In the study area, rainfall increased with increasing altitude of 186 mm per 100 m in 1999. Therefore, the rain gauge at the catchment outlet slightly underestimated rainfall for the whole catchment, for which could be corrected for the two subcatchments at an annual timescale.

Average streamflows per unit area of the entire catchment were generally larger than in the upper catchment during the winter period. In summer, streamflows were similar. Rainfall-runoff ratios also suggested a difference in discharge per unit area between both subcatchments.

During a dry period in the summer of 1999, discharge in the upper catchment declined to zero, whereas in the entire catchment, streamflow also decreased dramatically. This could indicate limited water storage space in the study area.

Flow duration curves from both weirs were similar and showed a steep rise in discharge with a frequency of less than 10% of the time. This also suggests limited potential to store water. In Section 5.5, the difference in discharge per unit area between subcatchments and the limited storage capacity will be discussed.

5.3 Storm event rainfall-runoff

5.3.1 Definition of storm event

Storm events were defined as single rainstorms producing a single, well-defined runoff peak to enable correct interpretation. The data used for this definition were based on a 15-minute resolution, in which rainfall figures were converted from 1-minute intervals to 15 minutes. Storm hydrographs consisting of more than one peak were left out of the analysis. The rain amount needed to be in excess or equal to 4 mm in a 4-hour period, as this was determined to be the minimum amount of precipitation needed in such a time period to create an easily identifiable peak from the hydrograph.

The start of the rise was the moment at which the first significant rise in discharge could be observed. The time of concentration was defined as the time between centre of mass of rainfall and peak flow (Black, 1991). The centre of mass of rainfall was determined by calculating the total amount of rainfall and determining the time at which half of the rainfall had fallen (Dunne and Leopold, 1978).

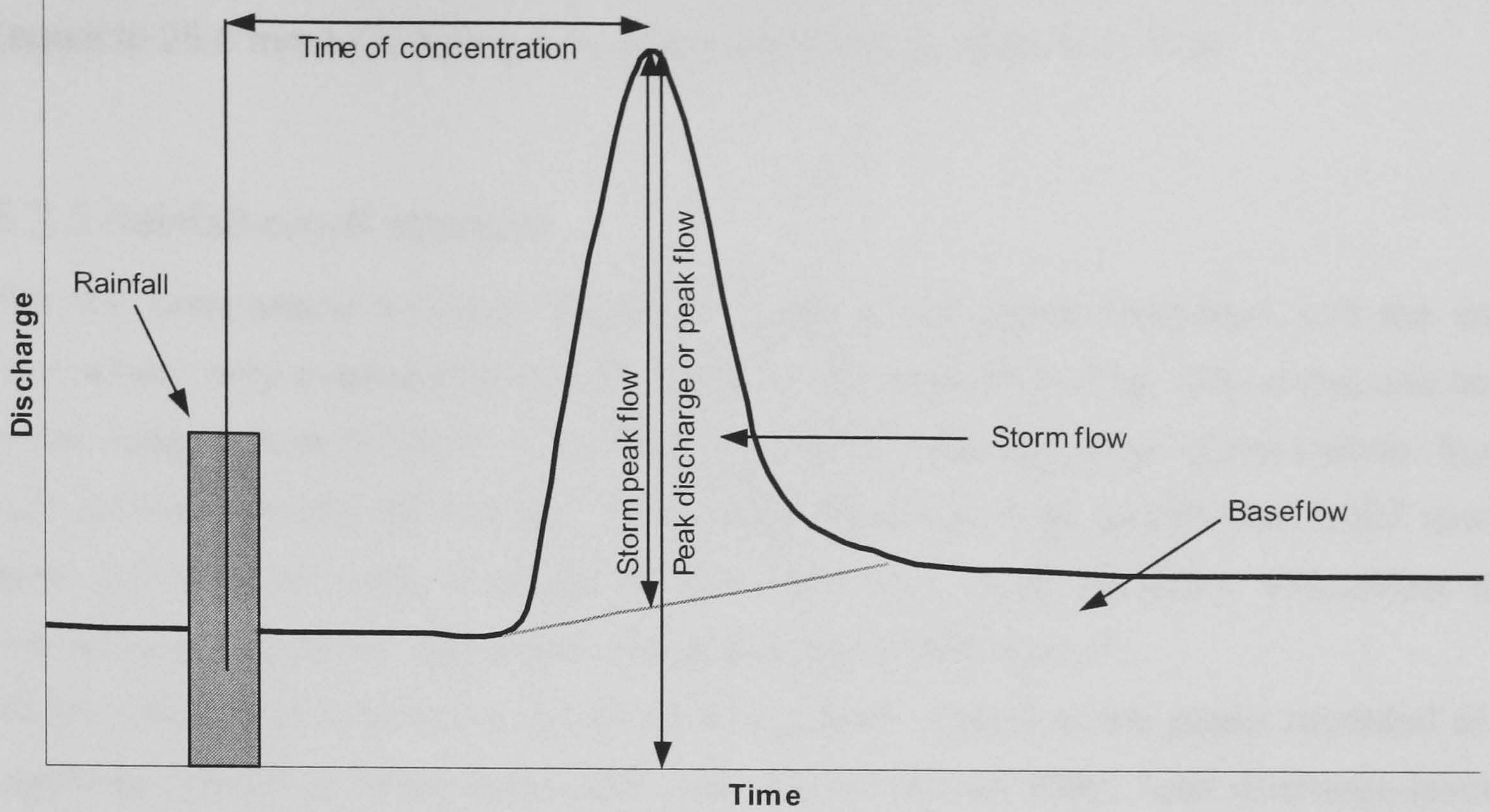


Figure 5.5: Definitions of terms used within the hydrograph (after Black, 1991).

The point at which the falling limb of the recession curve returned to baseflow was determined to be the point in time on which the discharge returned to a constant level for at least an hour (four consecutive recordings). A straight line was used to separate the storm flow and baseflow (Dunne & Leopold, 1978; Black, 1991; Tani, 1997). The same procedure was followed for each peak to ensure consistency. Storm flow was defined as the total volume of water discharged as a result of the rain event (Fig. 5.5), thus excluding the baseflow. Baseflow results from precipitation from an earlier rain event, which infiltrates into the soil and eventually moves through the soil to the stream channel (Black, 1991). Peak flow or peak discharge is the river discharge at the peak maximum (Dunne & Leopold, 1978; Black, 1991). Storm peak flow is the discharge at the peak maximum minus the baseflow.

5.3.2 Rainfall statistics

During the measuring period, 91 single rain events could be distinguished, which could be related to storm runoff. Rainfall amounts averaged 14.7 mm annually and ranged from 2.8 (in 60 mins) to 45.6 mm (10 hours) within one rain event. Average rainfall amounts per rain event were 13.7 mm in summer and 15.2 mm in winter. The average length of rainfall events was 4.30 hours (summer) and over 6 hours (winter). As a result, rainfall intensities were generally larger in summer than in winter. The average storm rainfall intensities was around 2.9 mm hr^{-1} and the maximum measured rain intensity was 6.4 mm in 15 minutes (equal to 25.6 mm hr^{-1}) during a two-hour rain event of 16.8 mm in total.

5.3.3 Rainfall-runoff statistics

For the comparison between discharge levels of the upper catchment and the whole watershed, only overlapping periods were used. Peak flows (Fig. 5.5) at the catchment outlet ranged from 0.025 to more than 5.5 mm hr^{-1} (flooding level of the Lothian flume), with an average of 0.52 mm hr^{-1}. Storm peak flows (Fig. 5.5) ranged from 0.007 to more than 5.5 mm hr^{-1} with a mean of 0.45 mm hr^{-1}. Initial baseflow, streamflow level immediately before the rain event, was averaging at 0.20 mm hr^{-1}.

At the headwater catchment, 49 single peaks were related to the peaks recorded at the catchment outlet between November 1998 and November 1999. Total discharge levels at the peak ranged from 0.033 to more than 2.66 mm hr^{-1} (flooding level of the weir) with an average of 0.45 mm hr^{-1}, which is the same as the average for the whole catchment. Initial baseflow was around 0.18 mm hr^{-1} and storm peak flow was about 0.27 mm hr^{-1} on average, ranging from 0.015 to 2.46 mm hr^{-1}.

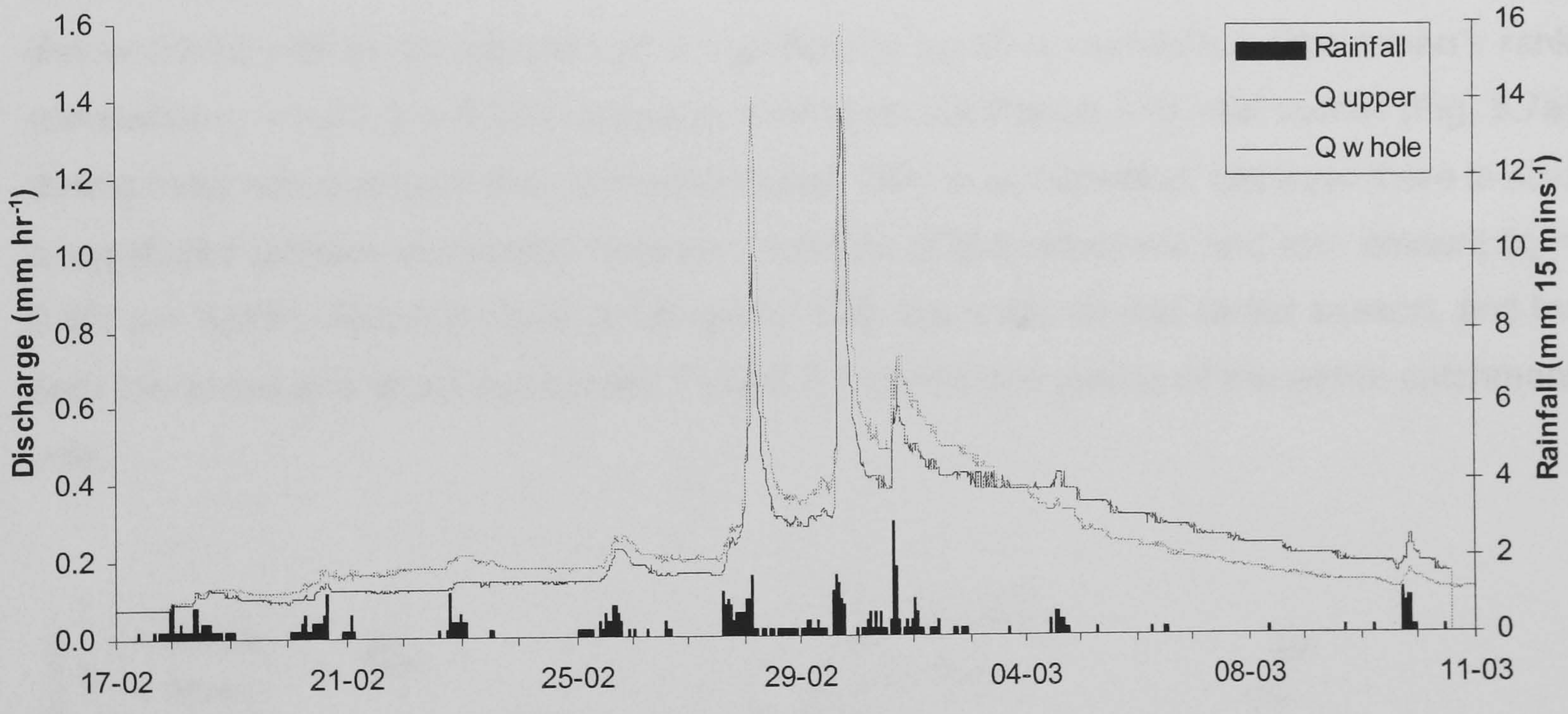


Figure 5.6: Example of rainfall-runoff curve of the whole catchment and the upper watershed for the period from the 17th of February to the 11th of March 1999.

The average time of concentration of the headwater catchment was similar to times of concentration at the whole catchment outlet, with values of around 92 mins, just 6 mins shorter than the whole catchment, which was shorter than the discharge recording interval of 15 minutes. Therefore, this difference in times of concentration between catchments is not significant. The average recession time of the headwater catchment was 8 hours and

40 mins, which is 40 mins longer than at the catchment outlet. A Kruskal-Wallis test showed that this also is not significantly different, indicating that the timing of peaks at both locations is the same.

When comparing average storm flow per unit area, it was shown that the whole catchment discharges 1.11 times the amount of the upper catchment in winter during storm events. In summer, no significant difference was found.

During large storms, stream discharge rose very rapidly by an order of magnitude at both weirs (Fig. 5.6). During such extreme events, catchment times of concentration were found to be on average about 98 mins and recession times were in the order of eight hours, suggesting that water is transported to the stream very rapidly. This has also been shown by the flow duration curves (Fig. 5.4). This 'flashy' behaviour is often found in peat-covered catchments (Weyman, 1974; Dunne and Leopold, 1978; Burt *et al.*, 1990). In many cases, this is attributed to a low remaining storage capacity (except after extraordinary dry periods) and because of low infiltration rates. Therefore, rainfall is quickly converted into overland flow, yielding a fast streamflow response (Burt *et al.*, 1990). However, in the study catchment, overland flow has only been observed locally in extremely wet situations, showing that the flashy response must mainly be a result of subsurface flow.

Below 20-25 mm of rainfall there is a significantly positive correlation (Spearman's rank correlation r_s = 0.63, p = 0.000) between time of concentration and total rainfall (Fig. 5.7a) during most rain events at the catchment outlet. This is as expected, because there is also a significant positive correlation between duration of the rainstorm and rain amount (r_s = 0.80, p = 0.000). This has been observed for both the summer and winter season, and for both the entire and upper catchment. Figure 5.7 shows the results of the whole catchment only.

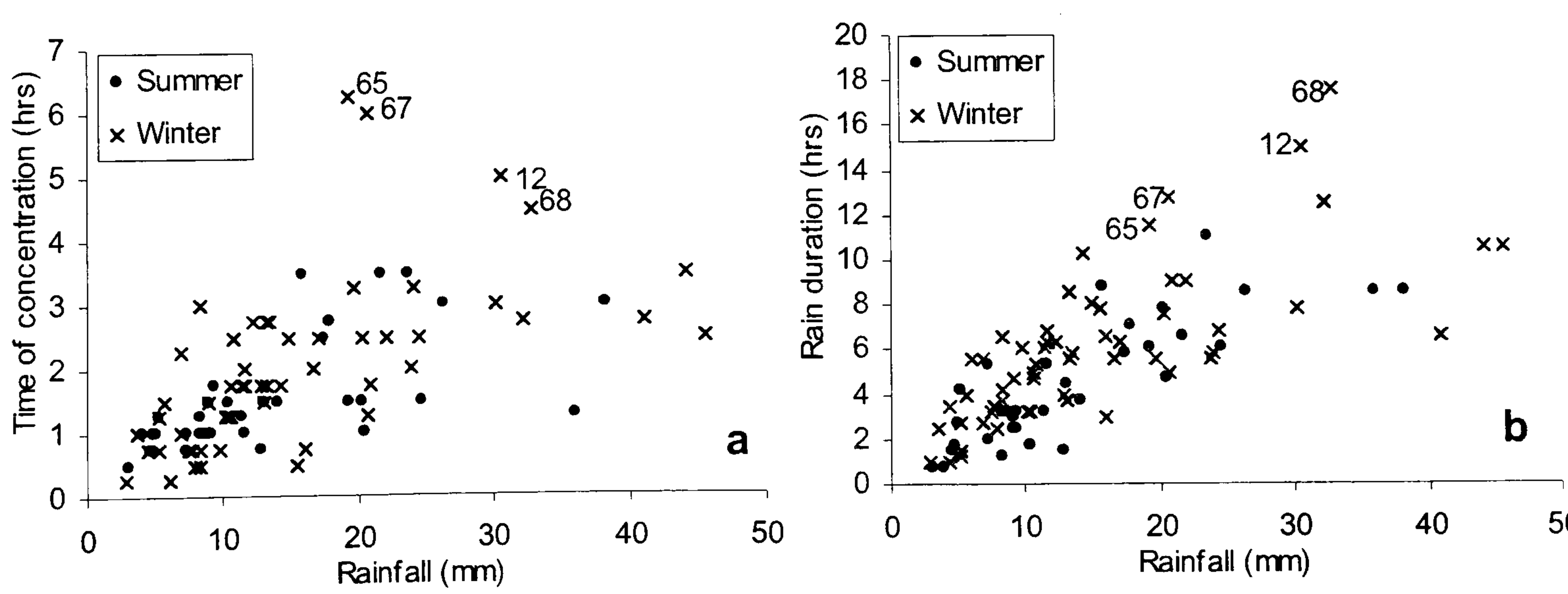


Figure 5.7: Time of concentration (a) and rain duration (b) vs. rainfall in the entire catchment.

Outliers indicated in Fig. 5.7, were extraordinary rain events during very specific conditions. Events 12, 65, 67 and 68 were unusually long events with medium to high rainfall amounts in wet conditions. In such an event, streamflow starts to rise quickly after the onset of precipitation, but due to the sustained intensity, discharge levels continue to rise until rainfall ceases.

During larger rainstorms of more than 20 to 25 mm in amount, the time of concentration appears to reach a maximum of around three to four hours (Fig. 5.7a). This is not a characteristic of the catchment, but is purely due to the limited time length of rainstorms in general, as is shown by the rain duration *vs.* rainfall in Fig. 5.7b. Therefore it can be concluded that the time of concentration is mainly a function of the characteristics of the rainstorm. Peak recession times were also positively correlated with rainfall amount (r_s = 0.61, p = 0.000), and rain duration (r_s = 0.65, p = 0.000) and were independent on initial discharge levels in both catchments.

5.3.4 Storm flow and rainfall amounts

The storm runoff volume or storm flow (total runoff volume minus baseflow volume, Black, 1991) *vs.* total rainfall relationship shows an exponential behaviour (Fig. 5.8). The curve can be divided into three sections. In the first section, during rainstorms smaller than 12 mm, storm runoff volumes are negligible in comparison to the rain amount. Runoff volumes are less than 5 % of the rainfall amount and most rainfall is stored in the soil. Larger rain events (> 12 mm) induce increasingly larger peak volumes in the second section, with a threshold around 20 mm.

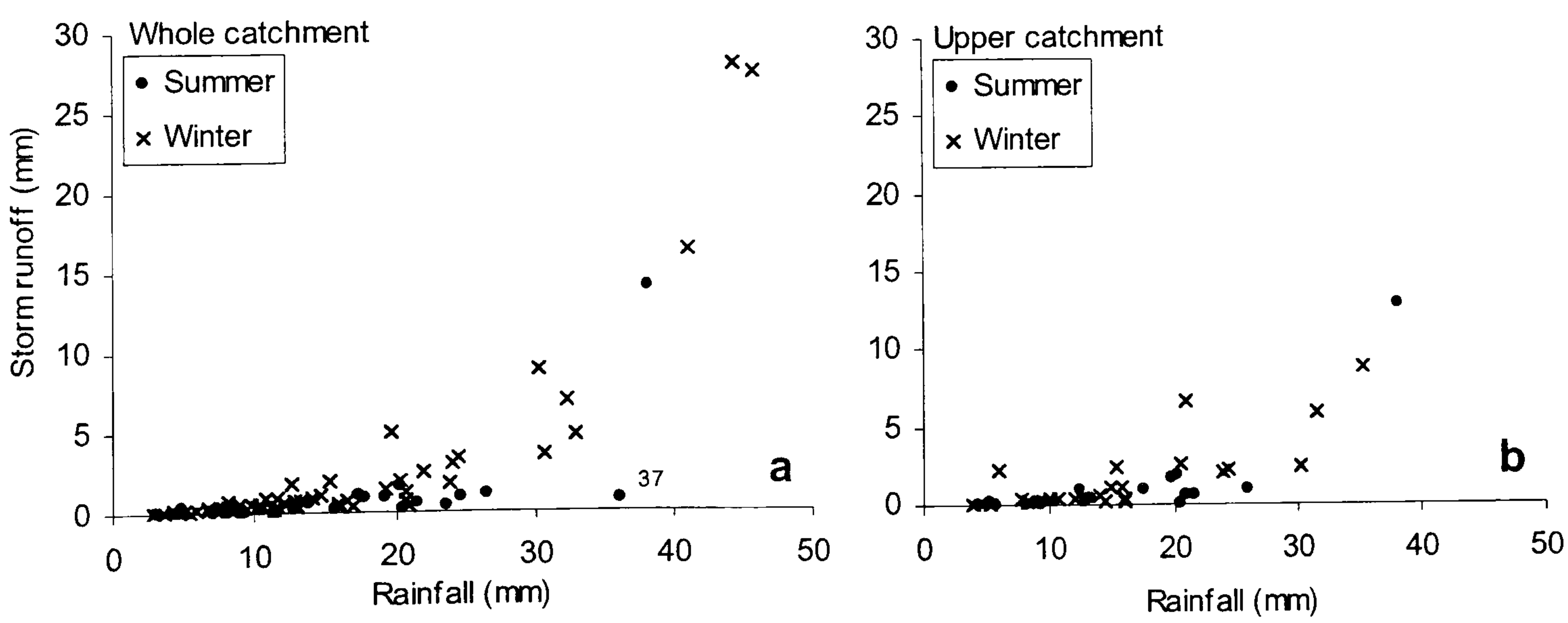


Figure 5.8: Storm runoff volume vs. rainfall in the whole (a) and upper catchment (b).

In the third section (> 20 mm) up to 65 % of the rainfall contributes to storm runoff (recorded during a rainfall event of 45 mm). This exponential relationship is dependent on seasonal variation, as storm runoff volumes in summer are on average less than half of that in winter. Differences can be attributed to the evapo-transpiration rates and lower antecedent moisture conditions due to less frequent and less voluminous rainfall during the summer period. The relationship could not be compared in the wettest section (> 20 mm), as these conditions rarely occur in summer.

The outlier of event 37 (Fig. 5.8a) represents an unusually intense summer rainstorm during dry antecedent conditions in which infiltration capacities are possibly exceeded, inducing more widespread overland flow than usual and hence a fast response in stream discharge.

A regression analysis was carried out between the storm flow, the total rainfall and initial discharge to determine the influence of antecedent wetness conditions (Equation 5.2). It was assumed that prior to the storm, the discharge was being predominantly supplied by groundwater and therefore the initial discharge could be used as a surrogate for antecedent conditions.

$$[5.2] \quad V_{storm} = 0.026 \cdot (1.16^{P} \cdot 47.7^{Q_i}) \qquad (R^2 = 0.85)$$

where:

V_{storm} = Storm flow (mm);

P = Total rainfall (mm);

Q_i = Initial discharge (mm hr^{-1});

Equation 5.2 shows that storm flow depends both on the total rainfall and initial discharge. Obviously, the total rainfall explains most of the variation (73%). The initial discharge also explains but statistically significant ($p < 0.05$) amount, albeit a relatively small percentage (12%). The regression analysis therefore showed that apart from total rainfall, antecedent wetness conditions play a significant role in the runoff generation in terms of volume.

5.3.5 Summary

Rain events in the area were on average about 5 hours, and rainfall intensities were generally larger in summer than in winter, with an average of about 2.9 mm hr^{-1}.

The rainfall-runoff response times of both outlets was not significantly different, with times of concentration averaging about 1.30 hrs, and recession times between 8 and 9 hours. Single peaks in discharge in the upper and entire watershed showed that the stream responds very quickly to rainfall, in accordance with the flow duration curve presented in Fig. 5.4. This behaviour is often observed in peat-covered catchments, due to low remaining storage capacity and low infiltration rates (Weyman, 1974; Dunne and Leopold, 1978; Burt *et al.*, 1990). Storm flow *vs.* total rainfall shows an exponential behaviour. Initially, rainwater is stored in the soil. As the storm progresses, a larger proportion of the water of the rain event is contributing to the runoff.

5.4 Catchment variability

Variations in size, topography, soils and vegetation might explain the subtle differences in discharge per unit area within the different catchments as shown in the previous sections. Hence, this section describes the upper catchment and the whole watershed in terms of topography, vegetation, and soils.

5.4.1 Physical features in the various catchments

Figure 5.9 shows the distribution of slopes of both the catchments, adjusted for the difference in catchment areas. Slopes in the headwater catchment tend to be steeper, contributing to lower topographic indices ($\ln(a/\tan\beta)$, Section 2.6.2) than the whole catchment. Topographic index values are generally lower in the upper catchment (Fig. 5.9). The lower index can be attributed to steeper slopes and smaller upslope contributing areas, partly due to the smaller catchment size. In terms of hydrology, areas with a high topographic index are wetter for longer periods of the year than areas with a lower topographic index, and are therefore more hydrologically active (Knapp, 1978; Whipkey and Kirkby, 1978; Church and Woo, 1990; Beven, 1997).

The vegetation composition in terms of percentage cover derived from air photos is very similar for the two catchments (Fig. 5.10), although it can be observed that the percentage of heather higher up in the catchment is higher, whereas bracken is lower in these areas. The full results of the vegetation cover will be described in Chapter 7 and 8.

However, the vegetation distribution within the catchments is not taken into account, *e.g.* distance to the stream and heterogeneity. In terms of interception this can be quite important. Several researchers have found that grass and heather species only intercept up to 1 and 2 mm of rainfall maximum, respectively, which is taken up mainly during the onset of the rainfall (Burt *et al.*, 1990). Williams *et al.* (1987) found higher values for bracken at 49% of the rainfall (20% on annual basis due to the natural growth cycle), which becomes more important the longer the duration of the rainfall.

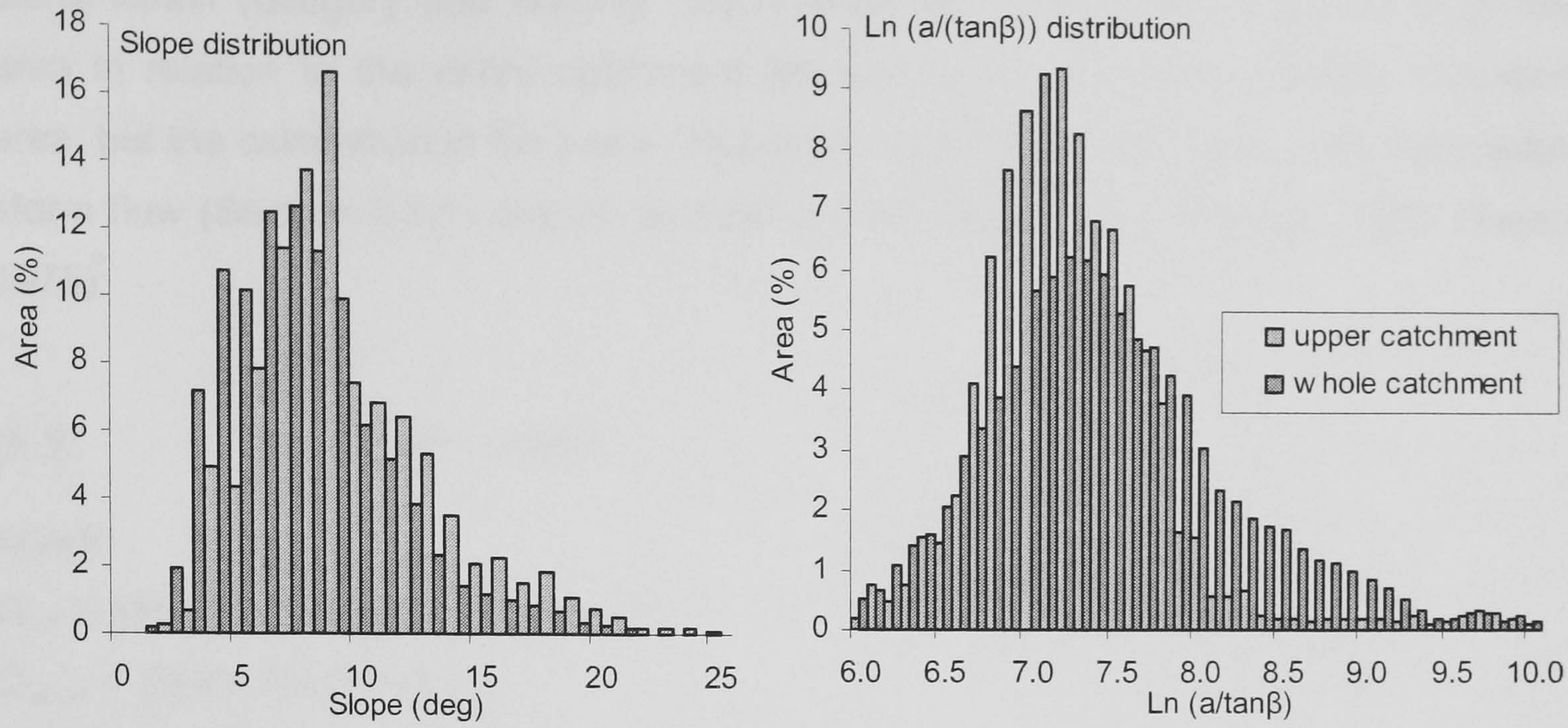


Figure 5.9: Slope and topographic index distributions.

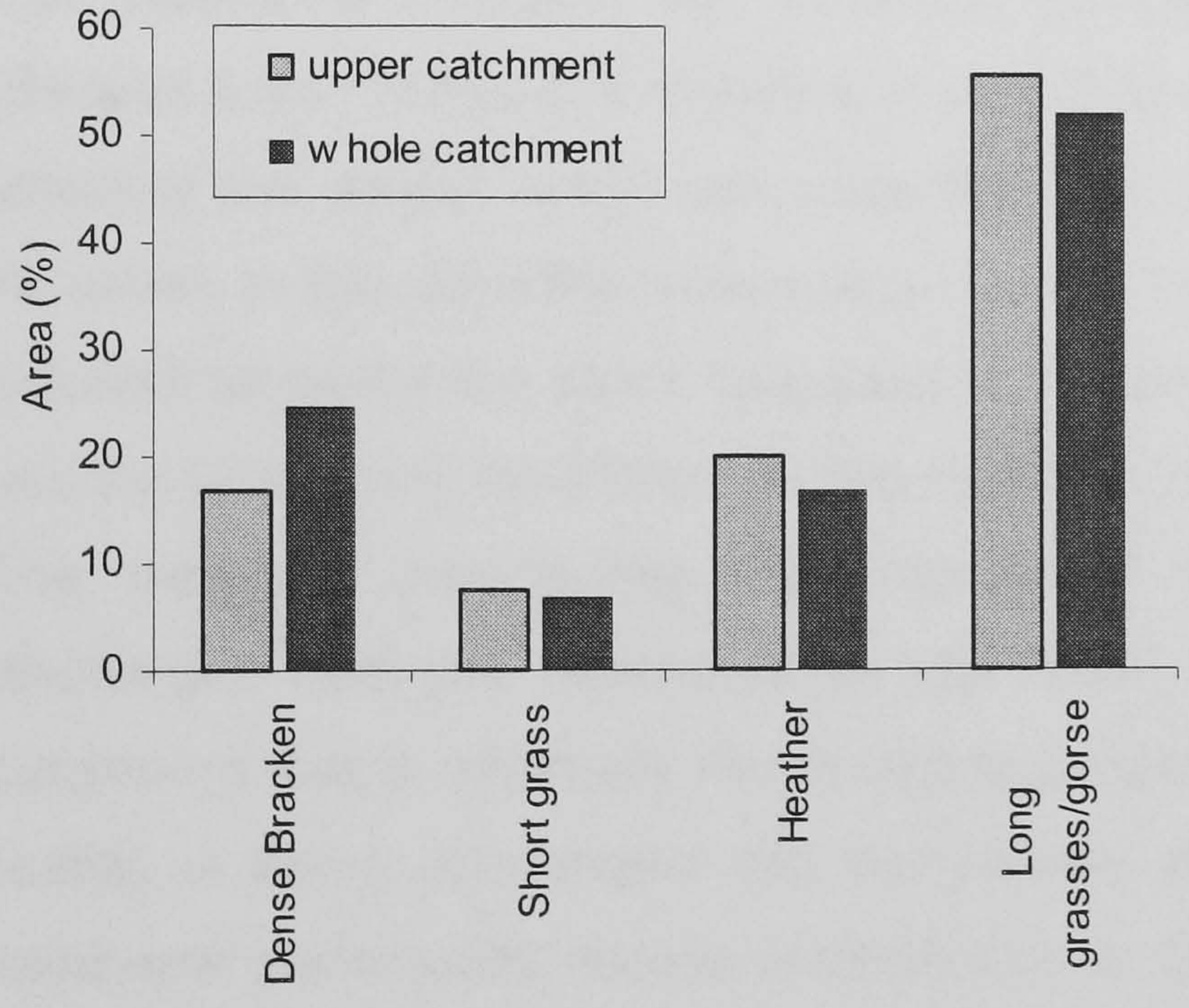


Figure 5.10: Percentage vegetation cover in upper and whole catchment.

The upper catchment also covers a substantial low sloping area on the fringe of the extensive peat bogs on the high plateaux of the moors. Soils in this area are deep peats (> 40 cm; Findlay *et al.*, 1984) and due to the peaty nature have a high porosity and high storage capacity. In the lower areas, the peaty topsoils are much thinner and therefore the soils have a lower storage capacity. This difference in storage capacity might partly explain the lower discharge levels per unit area from the upper catchment, which is discussed in Section 5.5.

5.4.2 Minimum contributing areas definition

The runoff percentage is defined as the proportion of the storm rainfall which occurs as storm runoff (Gregory and Walling, 1973). Weyman (1975) linked it to the proportional area in relation to the entire catchment and called this ratio the minimum contributing area, but the calculation is the same. The minimum contributing area can be calculated as storm flow (Section 5.3.1) divided by total rainfall (Gregory and Walling, 1973; Weyman, 1975):

[5.3] $$C_{\min} = \frac{Q_{storm}}{P} \times 100\%$$

where:

C_{min} = Minimum contributing area (%);

Q_{storm} = Storm flow (mm);

P = Total rainfall (mm).

The difference between the minimum contributing area and the rainfall-runoff ratio (Section 5.2.4) is that in the minimum contributing area calculation, the storm flow is used, whereas the rainfall runoff ratio uses the total runoff volume (storm flow plus base flow). However, in literature the terminology used is not always consistent. Different authors use different terms for the same calculations and vice versa. Brown *et al.* (1999) for example, use the term runoff coefficient for the minimum contributing area calculation.

The minimum contributing area represents the proportion of rainfall that is being discharged from the watershed as stormflow, and is equal to proportional area of the catchment that is minimally necessary to generate the storm runoff. It is assumed that all rainfall is being discharged into the stream. As this is often not the cause, the term 'minimum' contributing area is used (Weyman, 1974).

Thus, the minimum contributing area or runoff percentage can never be higher than 100%, both from a mathematical as well as a hydrological point of view, in contrast to the rainfall-runoff ratio.

5.4.3 Minimum contributing areas

In winter, minimum contributing areas were generally larger in the whole catchment than in the headwater catchment (9.0 and 8.1%, respectively). In summer, the area was the same for both catchments with an average of around 4.3%.

Consideration of the minimum contributing area (%) *vs.* total rainfall (Fig. 5.11) showed two types of response. At the catchment outlet, most rain events (less than about 20 mm, 77 recorded events) generated storm runoff with a minimum contributing area of less than 10%. Similarly, for the headwater catchment (33 recorded events) a minimum contributing area of up to 10% was calculated for the same rainfall amounts. The extreme values of event 1b and 13 (Fig. 5.11), both in winter, are attributed to high initial discharge levels, indicating high antecedent moisture conditions. Event 37 has been described in Section 5.3.4.

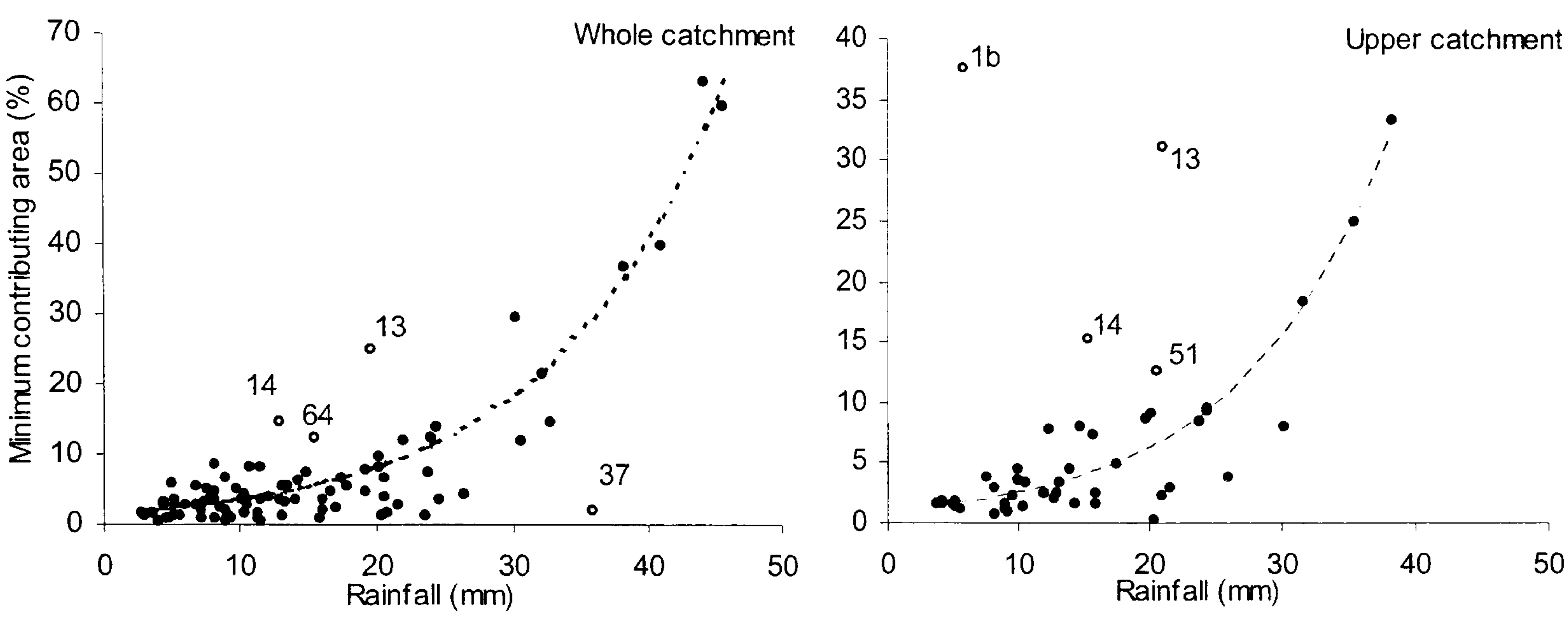
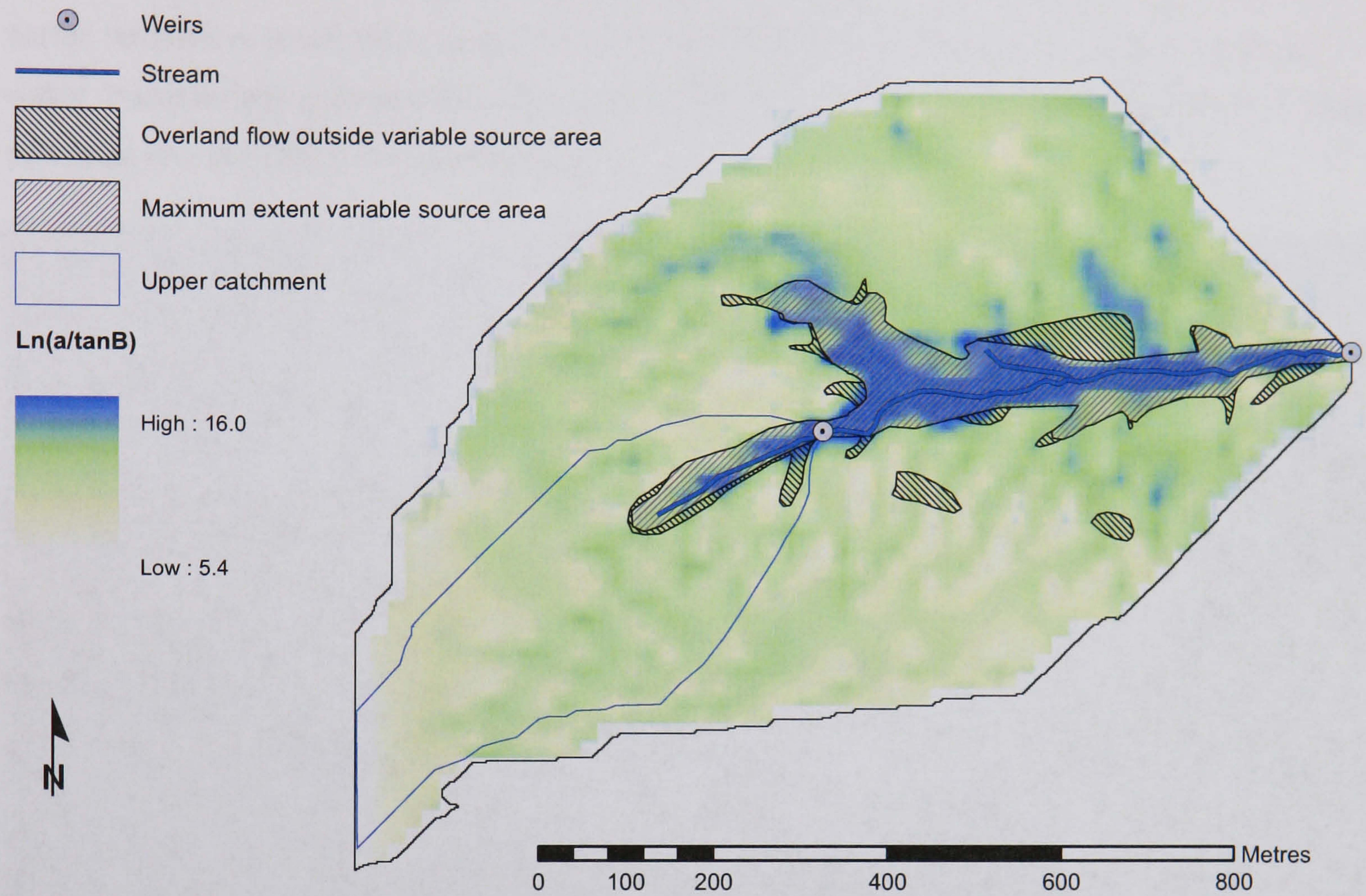


Figure 5.11: Contributing area vs. total rainfall.

Field observations have revealed a section (covering 8.6% of the whole watershed in very wet conditions) adjacent to the stream that is saturated throughout most of the year. This area, variable in size, was defined to be the variable source area. High topographic index values in the study area corresponded well with the field observations (Fig. 5.12). In the upper catchment, the variable source area was lower, with 6.8% of the area.

Minimum contributing area values of up to 10% in the whole catchment suggest that during smaller rain events, the variable source area is the main source of storm runoff. The difference between the calculations and field observations can be attributed to errors in rainfall and discharge measurements and possibly to sheep tracks locally contributing to overland flow and therefore peak runoff. Hence, during most rainstorms, this section adjacent to the stream is responsible for most of the water being discharged as storm flow into the stream, as suggested by Hewlett and Hibbert, 1967 (Section 2.6.1).

In modest to larger storms (more than 20 mm), the minimum contributing area increases more rapid with increasing rainfall. Weyman (1974) noted that the minimum contributing area does not increase considerably during most rain events, but only expands during extremely wet situations. Therefore, the minimum contributing area is often not linear with rainfall amount, and shows a threshold value above which the runoff increases exponentially. In such wet conditions, minimum contributing area values of up to 65% for the whole catchment and 38% for the headwater catchment have been observed. As these values indicate the minimum area contributing to storm flow, it is likely that the actual area contributing to the flow is larger. Hence, the area contributing to storm runoff must include a significant proportion of the slopes adjacent to the variable source areas.



The overland flow indicated on the map has been observed in the field during very wet conditions. Overland flow within the variable source area is also widespread. Note the correspondence between the variable source area and high topographic index values.

Figure 5.12: The variable source area superimposed on the topographic index map.

A similar effect of increased minimum contributing area value by increased catchment size was observed by Brown *et al.* (1999) in a similar approach of nested catchments as presented in this thesis. However, they could not explain this phenomenon.

During summer, minimum contributing areas are significantly lower than during the winter period. Due to higher evapo-transpiration rates and less rainfall, a higher proportion of the precipitation is used as storage in the soil than in winter, yielding lower runoff values and therefore a lower minimum contributing area. This suggests that antecedent moisture conditions (*i.e.* soil moisture) play a major role in the extent of minimum contributing areas.

Within the study catchment, is has been noted that during wet conditions, overland flow within the variable source area is widespread (Plate 5.1). Field visits to the study area have confirmed that the saturated areas adjacent to the stream can expand slightly during storms (Fig. 5.12). However, there is no evidence of wide scale infiltration excess (Hortonian) or saturated overland flow outside these areas during all but the most extreme rain events, and even in these cases overland flow has only been observed locally. This in combination with contributing areas on to the steeper slopes indicates, that subsurface water relocation must be a major factor in storm flow generation. In order to analyse the water transporting process through the soil, the velocities associated with this soil water pathway are studied in the next section.

Plate 5.1: Overland flow as observed in the variable source area (lower catchment).

5.4.4 Hillslope water average travel times and velocities

When the minimum contributing area is divided by the length of the stream, an estimate of the average effective slope contributing to the runoff can be established (Dowd, 2000, pers. comm.). Subsequently, if this average distance is divided by the time of concentration, average water transport velocities down the slope can be estimated.

Within the watershed, a minimum contributing area of 10% equals an average effective upslope length of 36 metres. During wet conditions, effective upslope lengths have been estimated from 42 up to 228 metres. Associated average velocities are variable and are calculated to range from 8.6 to 89.4 m hr^{-1}. These velocities are high, and are normally associated with overland flow (Dunne, 1978; Emmett, 1978) or pipeflow (Gilman and Newson, 1980; McCaig, 1981.) These findings are combined with soil moisture results and discussed in the final section of Chapter 6.

5.4.5 Summary

As it has been shown that there are subtle differences in discharge per unit area between the upper and the entire catchment, physical features of both catchments were compared. Generally, the slopes in the upper catchment are higher and topographic index values are lower than the whole area. The heather cover is slightly higher at higher altitudes, with a lower bracken cover, as shown by air photos. Bracken can be associated with high interception in summer, whereas in winter this negligible, as the plant dies back.

Although the slopes in general are steeper in the upper catchment, the soils in this area near the plateau are characterised by relatively deep peat soils, and have a high storage capacity.

Field observations have shown that overland flow has been observed to be widespread in the valley floor, but on the hillsides this rarely occurs. These observations combined with the minimum contributing area results, indicate that with increasing rainfall and wet antecedent conditions water moving down the slope is mainly transported through the soil. Velocities associated with the water transport during larger storms are relatively high. They are comparable with velocities normally associated with overland flow (which does not occur on a large scale on the hillsides in the study area) and pipeflow.

5.5 Runoff generating processes at the catchment scale

Storm flow is generated by several different processes in the study area. In most cases, during low to medium amount rain events (< 20 mm), the variable source area in the valley floor is the main contributor to storm flow. Field observations have shown, that overland flow is widespread in the valley floor. Minimum contributing area calculations revealed a maximum of around 10% of the catchment area, which corresponds well with the extent of the saturated area observed in the field, defining the variable source area. Therefore, saturation excess overland flow is an important factor in runoff generation during these low to medium rain events. Rainfall-runoff and flow duration curves showed that the stream responds quickly to rainfall. Times of concentration were in the order of one to two hours. Velocities that are normally associated with overland flow are in the same order of the times of concentration observed in the area.

During larger storms (> 20 mm), the variable source area is still of main importance to the runoff generation. However, minimum contributing area calculations showed, that a much larger proportion of the catchment area must be contributing in order to account for the large storm flow. Values of up to 65% of the area have been calculated. However, the absence of overland flow on the steeper slopes prohibits the same process as during smaller rain events. Hence, a large proportion of the event water on the hillslopes must be transported through the soil as subsurface flow. This would suggest a response time longer than if water is transported as overland flow. However, times of concentration during these conditions remained high, as were the velocities associated with the storm runoff. These velocities, in the order of 9 to 90 m hr^{-1} are normally attributed to overland flow or pipeflow.

A regression between storm flow, total rainfall and initial discharge showed that the characteristics of the rain event were of main importance to the storm flow. The initial discharge prior to the event, a measure of antecedent wetness conditions, also played a significant role in the runoff generation.

After rain events, the stream quickly returns to baseflow levels, with average recession times in the order of eight to nine hours. So it was assumed that in non-storm conditions, the discharge is predominantly supplied by groundwater. Possibly, soil water from the variable source area also contributes to the baseflow as subsurface flow, as no overland flow has been observed during these conditions. The water holding capacity of the soil layers supplying this water is probably limited, however. It was shown that after a relatively short dry period in the summer of 1999, discharge levels decreased dramatically. In the upper catchment, measured discharge levels in the stream even declined to zero for a short period. Hyporpheic flow was still contributing to discharge of the whole catchment during this period.

In winter, the whole catchment discharges more water per unit area than the upper catchment. In summer, the discharge per unit area in both catchments is more or less equal. This has not only been observed on a seasonal time scale, but also for individual storms.

This is in correspondence with the findings by Brown *et al.* (1999), who showed that in a nested catchment (8 to 161 ha) approach in New York State (US), peak runoff and runoff coefficients increased with area. However, these findings are in contrast with a literature study by Dunne (1978), who showed that generally in humid climates, larger catchments discharge less water per unit area than smaller catchment. This was attributed to the longer distance to the stream in larger catchments.

Topographic analyses have shown that slope angles are generally lower in the lower part of the catchment. Normally, this would suggest that discharge levels per unit area in the headwater catchment should be higher, as lateral water flow increases with increasing gradient (Knapp, 1978). However, a larger proportion of relatively flat areas adjacent to the stream have been observed in the whole catchment. These areas were defined as the variable source area. In the upper catchment, the variable source area covers about 6.8% of the area, and in the whole catchment, this figure is 8.9%. The proportional difference in variable source area between catchments therefore could explain the larger amount of runoff per unit area. Indeed, the ratio of whole catchment storm flow over upper catchment storm flow in winter is about 1.11 (Section 5.3.3). The ratio of average long-term discharge is slightly larger, around 1.44. These values are comparable to the ratio of variable source areas between catchments (1.31). The difference in discharge levels is largest in winter, because the variable source area is using its full potential: the area is close to saturation and evapo-transpiration is at its minimum. During summer, however, more losses occur due to reduced storage levels and evapo-transpiration and therefore reducing the difference between catchments. The extent of the saturated areas and the difference in vegetation cover could therefore be contributing to the difference in discharge per unit area.

As shown in Section 5.2.6, the flow duration curve suggests that the study area has a low storage capacity (Weyman, 1975) and the minimum contributing area analysis also shows that storage capacity and antecedent moisture conditions play an important role in the rainfall-runoff response. Although peat soils in general have a high porosity and therefore a high storage capacity, soils in the lower parts of the study area are relatively thin and are close to saturation most of the year. The proportion of peat soils near the top of the plateau is higher (Findlay *et al.*, 1984) and these peats are generally deeper than lower in the catchment, increasing the storage capacity in the upper catchment. This could also partly explain the lower discharge per unit area in the upper catchment.

However, higher transpiration rates of grass compared to heather (Gimingham, 1975) would suggest that the headwater catchment, having a more extensive grass cover, would have to discharge more water per unit area. Moreover, heather and grass have a lower interception than bracken in summer (Burt *et al.*, 1990; Williams *et al.*, 1987; Section 5.4.1), suggesting higher discharge levels in the upper catchment in summer, as bracken dies back in winter (Williams *et al.*, 1987). If the difference in size of the variable source is the main factor in the difference in discharge between catchments, the bracken cover in summer possibly contributes to a levelling out of the difference in discharge. However, the interception process probably is too complex to explain runoff difference between subcatchments. The temporary storage of water in the plant canopy depends on the matrix and density of the vegetation (Ward and Robinson, 2000). Therefore, not only the plant species will determine rainfall interception (Newson, 1997), but also the growing stage (Gimingham, 1975), season (Williams *et al.*, 1987; Johnson, 1990) and grazing levels will be of main importance.

So, the smaller extent of the variable source area and the higher proportion of deep peats in the headwater catchment could explain the difference in discharge per unit area from the catchments. The temporal variation in soil wetness and vegetation cover also have their effect on the difference, but the latter is difficult to quantify.

From the results presented in this chapter and knowledge of the soils as described in Chapter 4, it is clear that attention must be focussed onto shallow subsurface flow, storage capacity and antecedent wetness conditions. The next chapter will focus on the processes and variation on hillslope scale in order to determine the most important processes in soil water transport.

Chapter 6: Spatial variability and hillslope water pathways

6.1 Introduction

This chapter deals with the relationship between soil moisture variability, topography, soil characteristics and stream discharge. The main objective is to create an understanding of the main hillslope water pathways, based on the findings presented in this and the previous chapter. The chapter is structured as follows:

- In Section 6.2 the topography within the TDR-grid will be outlined.
- Section 6.3 describes the different soil profile characteristics, both at point and hillslope scale within the TDR-grid.
- In Section 6.4, the relationship between soil moisture, topography and the soil profile will be outlined. The main focus will be on that part of the hillslope covered by the main TDR-grid, but the section will also analyse the representativeness of this area in relation to the typical Dartmoor soil catena, the entire hillslope and the catchment as a whole.
- In Section 6.5, the influence of spatial soil moisture distributions on stream discharge will be described. Soil moisture will be used as a indicator for antecedent wetness.
- Section 6.6 will analyse the temporal behaviour of soil moisture and pressure heads in the soil profile. The relative importance of vertical water movement in comparison to the lateral component will be established.
- In the last part (Section 6.7), the results of this and the previous chapter are combined into a conceptual model of soil water pathways at the hillslope scale.

6.2 The topography of the main TDR-grid

The altitude within the TDR-grid ranges from 350 to 420 m above sea level (0 to 70 m above the stream). Slope angles vary from 0° to 18°. The slope profile of the hillslope can be divided into three parts, with the plateau and the valley floor separated by a steeper section (Fig. 6.1). The convex plateau extends from 200 to 400 m from the stream. The shoulder is positioned at around 170 m distance, followed by a short steep straight slope, which levels out into a concave area down to 100 m from the stream. A relatively level area near the stream takes up the remainder; it was disturbed in the past by tin-streaming, lowering the ground surface level for one or two metres in the valley bottom.

Slope angles and topographic index values (Section 4.6.1) were derived from a 10 m resolution DEM and values were consequently transferred to the corresponding TDR-grid points using a GIS. Descriptive statistics of the topography are given in Table 6.1.

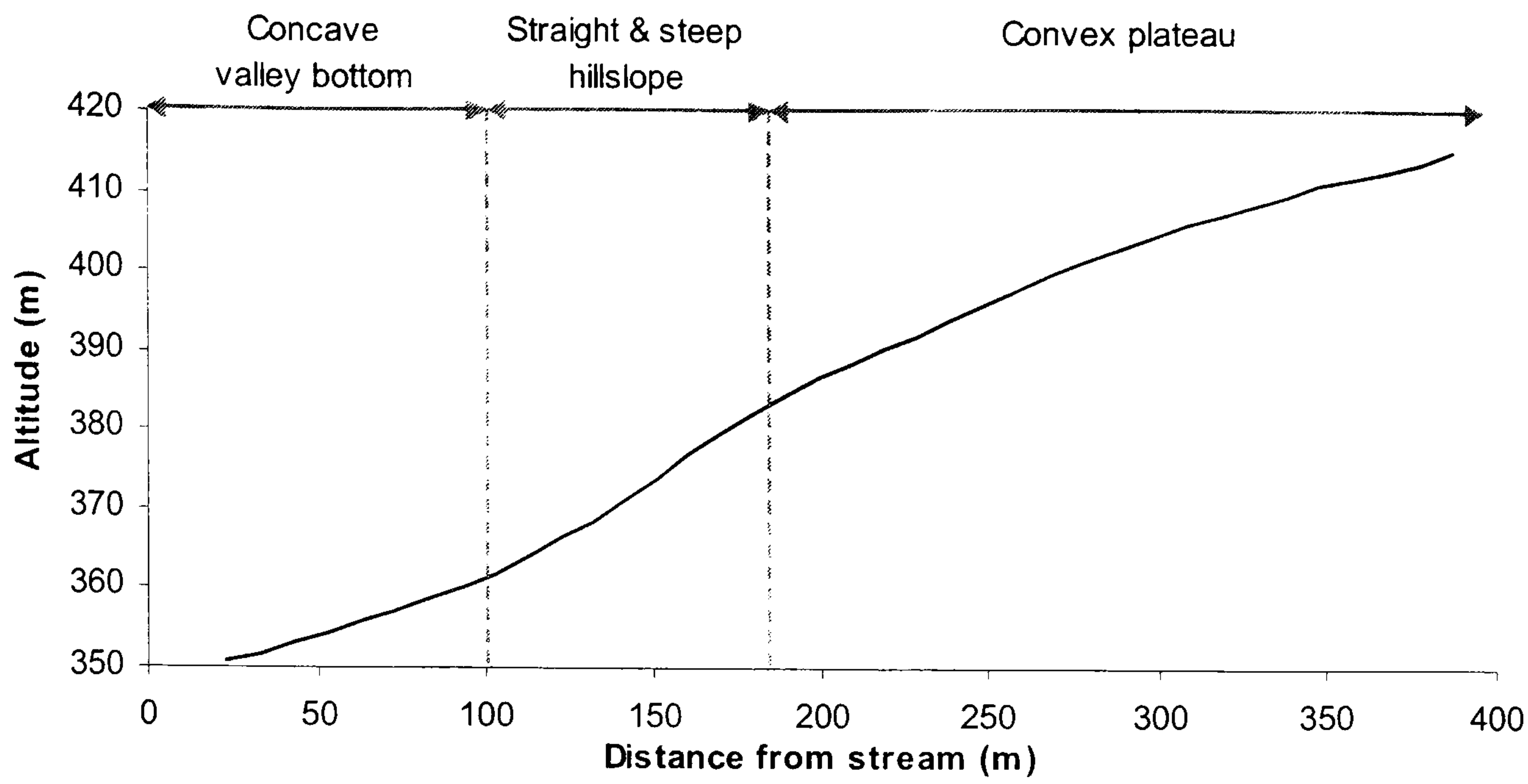


Figure 6.1: Hillslope profile of the TDR-grid.

Table 6.1: Descriptive statistics of the topography within the TDR grid.

	Altitude (m)	Slope angle (°)	Ln(a/tanβ)
Mean	384	9.6	7.1
Min	350	2.0	4.9
Max	416	17.0	14.9
n	151	151	151

6.3 Soil profile characteristics at the point and hillslope scales

As described in Chapter 4, a range of soil properties were analysed and soil profiles described in the field at 23 different locations within the TDR-grid. This section focuses on the soil profiles in general, as well as the point scale relationships between the analysed soil properties in order to understand the variability of soils across the hillslope. First, the soil catena of the hillslope will be outlined in detail, including the relationships with soil moisture contents and the topsoil. The catena will also be compared to the 'typical' Dartmoor catena. Second, the measured soil properties will be described.

6.3.1 The soil catena

Figure 6.2 shows the catena of the different soil profiles described within the TDR-grid. The catena covered a distance of around 400 m. All described profiles within the catena had fibrous (Of) or semi-fibrous (Oh) peaty topsoils, between 5 and 40 cm in thickness, in some locations subdivided into different horizons. Thickness varied greatly, but a tendency towards more fibrous topsoils near the top of the slope and the valley floor could be distinguished. Midslope the semi-fibrous topsoils were more common (Fig. 6.2). Although raw peat soils and humic rankers are classified as separate soil series, within the described catena the soil types were similar. The main difference is the depth of the peat, with rankers typically being equal or less than 30 cm deep (Soil Survey, 1984). These rankers mainly occurred locally and were mostly formed on shallow rocks in the subsoil. Most raw peat soils and humic rankers were found in the more level areas near the top and in the valley. Ironpan stagnopodzols occurred locally throughout the catena. Stagnohumic gley soils were only found in the lower half of the hillslope.

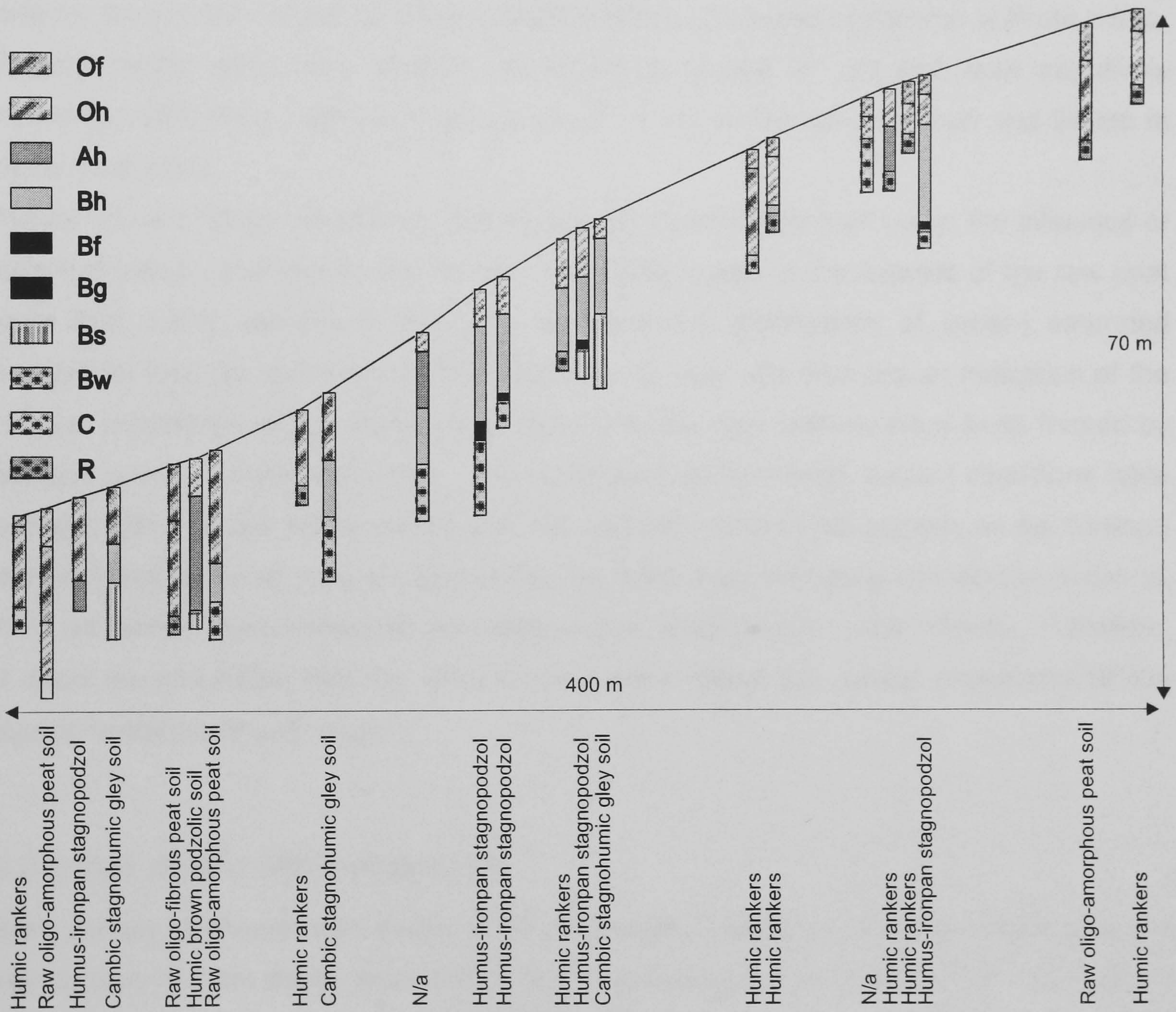


Figure 6.2: Soil catena within the soil moisture grid.

The catena was fairly typical for the average Dartmoor hillslope, with fibrous or amorphous peat soils near the top and foot of the slope, ironpan stagnopodzolic soils mainly near the shoulder and humic brown podzolic soils on the steepest hill slopes (Fig.

3.4 and Findlay *et al.*, 1984). In the study area however, stagnohumic gley soils were not found just below the highest parts of the plateau, but lower on the hillslope. Also, brown podzolic soils were found less frequently than in the typical Dartmoor catena.

The soil distribution also compared reasonably well with the less detailed (scale 1:25,000) soil associations map of Hogan (1988), which were typified by high groundwater tables or lateral seepage on the slopes and by wet peaty topsoils near the bottom, often with a thin ironpan. Due to their development in better drained soils, ironpans are generally not found near the wet foot slopes on Dartmoor. However, because of past tin mining in and near the stream, the riverbed and surrounding area is altered, leaving a small ridge one to two metres in height on both sides of the stream. Due to this feature, soils are much better drained than under natural conditions and therefore, an ironpan could form in these areas.

Topsoil depths were fairly shallow, averaging at around 21 cm and were negatively correlated with slope, with average values of 15 cm on the steepest part and 24 cm in more level areas.

Nearly all soils within the catena can be typified as having formed under the influence of near-saturated conditions in the topsoil. The peaty nature of the topsoils of the raw peat soils and humic rankers in the area all show the significance of (near-) saturated conditions near the soil surface. The stagnohumic gley soils also are an indication of the relative importance of soil water in the topsoil, as the gley features have been formed by surface water. In some soil series, due to the past soil formation, current conditions have a major effect on soil water distribution. For example, most of the podzols on the hillslope are now typified by an ironpan, preventing the water from infiltrating into deeper horizons. This will have a great impact on the lateral water redistribution on the hillslope. Therefore, it could be concluded that the soils in the catena reflect the natural importance of the topsoil to soil water pathways.

6.3.2 Bulk density and total porosity

Bulk density increased with depth at all 23 sampled locations. Average values near the soil surface (0-3 cm depth) were 0.25 g cm^{-3}, increasing to 0.76 g cm^{-3} at 16-19 cm depth. Other researchers found similar values for organic soils (*e.g.* Munro, 1982; Koorevaar *et al.*, 1983; Marshall and Holmes, 1988). Standard deviations of the bulk density also increased with depth, showing an increase in variability with depth (Table 6.2). The minimum bulk density found was 0.13 g cm^{-3}, near the soil surface, with a maximum value found of 1.35 g cm^{-3}, at 16-19 cm depth, which is a value typical for mineral soils.

Table 6.2: Descriptive statistics for bulk density and total porosity.

	Bulk density (g cm^{-3})				Total porosity (cm^3 cm^{-3})				Transmission pores (cm^3 cm^{-3})			
Depth (cm)	**0-3**	**4-7**	**12-15**	**16-19**	**0-3**	**4-7**	**12-15**	**16-19**	**0-3**	**4-7**	**12-15**	**16-19**
Mean	0.25	0.35	0.61	0.76	0.90	0.86	0.77	0.71	0.25	0.22	0.20	0.19
Min	0.14	0.14	0.14	0.13	0.83	0.74	0.51	0.49	0.13	0.10	0.10	0.12
Max	0.52	0.70	1.30	1.35	0.97	0.98	0.96	0.97	0.40	0.33	0.35	0.28
St. dev.	0.10	0.13	0.31	0.39	0.04	0.06	0.12	0.14	0.09	0.06	0.06	0.05
coeff. of var.	0.41	0.39	0.51	0.51	0.05	0.06	0.16	0.20	0.36	0.27	0.30	0.24
n	22	22	21	21	22	22	21	21	22	22	21	21

Total porosity, calculated from the saturated cores (Section 4.4.4) ranged from 0.90 cm^3 cm^{-3} near the soil surface to 0.71 cm^3 cm^{-3} at 16-19 cm depth. The minimum porosity measured was 0.49 cm^3 cm^{-3}, a value typical for mineral soils (Koorevaar *et al.*, 1983), with a maximum value of 0.98 cm^3 cm^{-3}. Although this seems high, porosity values reaching typical values of 0.90 to 0.95 cm^3 cm^{-3} in organic soils have been reported by Munro (1982), Pepin *et al.* (1992) and Roth *et al.* (1992). As with the bulk density, standard deviations of the total porosity increased with depth (Table 6.2).

The transmission pore volume (i.e. pores > 50 μm, Rowell, 1994) decreased with depth from 0.25 cm^3 cm^{-3} to 0.19 cm^3 cm^{-3} on average. Most variation was found in the topsoil, as the standard deviation decreases with depth. The minimum volume of transmission pores is around 0.10 cm^3 cm^{-3}, whereas the maximum is up to 0.40 cm^3 cm^{-3} of the soil volume. Data from Munro (1982) for peat soils showed a similar average of around 0.20 cm^3 cm^{-3}, but with a high degree of variation, due to its highly variable origin. Section 6.3.4 describes the porosity distribution in more detail, using the soil water release curve.

6.3.3 Organic matter content

Organic matter content, measured by loss-on-ignition (l.o.i.; Section 4.4.4) showed a wide range of values (Table 6.3). In general, the organic matter content decreased with increasing depth, ranging from 78.1 g $100g^{-1}$ near the soil surface to 25.9 g $100g^{-1}$ at 16-19 cm depth. The Soil Survey (1976) defined a soil horizon to be peat if the organic matter content is higher than 20 g $100g^{-1}$ in sandy soils (40 g $100g^{-1}$ in clay). Soils on Dartmoor naturally have high sand and low clay fractions (Findlay *et al.*, 1984; Gerrard, 1989). This means, that in general the top 20 cm of the soil could be classified as peat. However, in some cases, especially between 10 and 20 cm depth, the horizons should be regarded as mineral soils. The maximum organic matter content was 93.0 g $100g^{-1}$, and the minimum was found to be 4.1 g $100g^{-1}$, which is close to that of mineral topsoils (Koorevaar *et al.*, 1983; Droogers *et al.*, 1997). Standard deviations generally increase with increasing depth.

Table 6.3: Descriptive statistics for the organic matter content.

	Organic matter content (g/100 g dry soil)			
Depth (cm)	**0-3**	**4-7**	**12-15**	**16-19**
Mean	78.1	62.0	40.9	25.9
Min	42.2	19.8	5.1	4.1
Max	93.0	91.0	91.5	78.7
St. dev.	14.4	18.4	27.3	24.4
coeff. of var.	0.18	0.30	0.67	0.94
n	23	23	22	22

Table 6.4 shows the correlation matrix between organic matter content and slope angle, average soil moisture content (as measured with TDR on 19 occasions), bulk density and total porosity. The sampling size was 21 and due to the non-normally distributed data set, a Spearman ranked correlation (correlation coefficient r_s) was used.

The organic matter content averaged over the top 20 cm showed a negative correlation with slope angle, and was positively correlated with average soil moisture content (Table 6.4). Deeper in the soil profile, the correlation between organic matter content, slope angle and soil moisture became increasingly more significant.

Table 6.4: Spearman ranked correlations between organic matter content and dry bulk density, porosity and gradient.

	om_{0-20}		om_{0-3}		om_{4-7}		om_{12-15}		om_{16-19}	
	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
Gradient	-0.49	0.025	-0.16	0.466	-0.38	0.079	-0.45	0.041	-0.51	0.020
$\theta_{average}$	0.52	0.017	0.22	0.314	0.46	0.035	0.56	0.010	0.55	0.012
ρ_{0-20}	-0.89	0.002								
ρ_{0-3}			-0.49	0.026						
ρ_{4-7}					-0.71	0.001				
ρ_{12-15}							-0.71	0.001		
ρ_{16-19}									-0.92	0.000
Φ_{0-20}	-0.88	0.000								
Φ_{0-3}			0.33	0.317						
Φ_{4-7}					0.63	0.004				
Φ_{12-15}							0.74	0.001		
Φ_{16-19}									0.94	0.000

$n = 21$, $p < 0.05$

ρ: dry bulk density (g cm^{-3}), Φ: porosity (cm^3 cm^{-3}), om: organic matter content (loi, g 100 g^{-1}), gradient (°)

Values indicated in grey are not significant

This is a reflection of the past soil-forming environment. Highly organic soil horizons on Dartmoor have formed in relatively wet conditions (Findlay *et al.*, 1984). Lower slope angles increase soil water contents due to decreased drainage (Dunne, 1978; Black, 1991; Quinn *et al.*, 1995) and wet conditions consequently decrease vegetation decomposition rates, increasing the organic matter content of the soil (Rowell, 1994;

White, 1997). Within the catchment, steeper slopes were generally better drained and therefore had lower soil moisture contents (r_s = -0.27, p = 0.001, n = 151) and therefore showed less organic material build up.

However, the top layer is still being affected by present day soil formation and other more short-term factors like management and vegetation (change) and therefore reflects the complexity of many influences. This top layer had a lower variability, and therefore showed a non-significant correlation between organic matter, gradient and soil moisture.

Because of the low bulk density of organic material, typically around 0.20 to 0.25 g cm^{-3} (Munro, 1982) as opposed to 1.4 to 1.6 g cm^{-3} in mineral soils (Koorevaar *et al.*, 1983; Marshall and Holmes, 1988), dry bulk density of the soil was negatively correlated with organic matter content. Consequently, organic matter was positively correlated with the porosity. Hence higher organic matter contents indicate higher soil water storage, which was shown to be significant only when deeper than 3 cm in the profile (Table 6.4).

Organic matter contents were also compared to saturated hydraulic conductivity values. However, the measured variability was so large within the conductivity measurements, that no significant relationships between organic matter content and K_{sat} or log K_{sat} could be identified (See also Section 6.3.5).

6.3.4 The soil water characteristic curve

Figure 6.3 shows the water release curves averaged over the top 20 cm for 19 different locations sorted by increasing organic matter content. The curve was plotted on a linear soil suction scale. The general shape of the curve showed a distinctly different slope at near-saturation in comparison to the lower suctions. This result suggests a relatively high fraction of transmission pores, determined by the 0-50 cm suction interval (Rowell, 1994). Similar results on a peat soil were obtained *in situ* by Munro (1982), in which field soil moisture contents of the top 10 cm were plotted against the depth of the water table (H) ranging from 0 to 70 cm. Although in his paper, Munro (1982) fitted a linear regression line to the relationship between soil moisture and H, an obvious break in slope could be identified at a soil suction of around 20 to 30 cm, which is similar to results presented here.

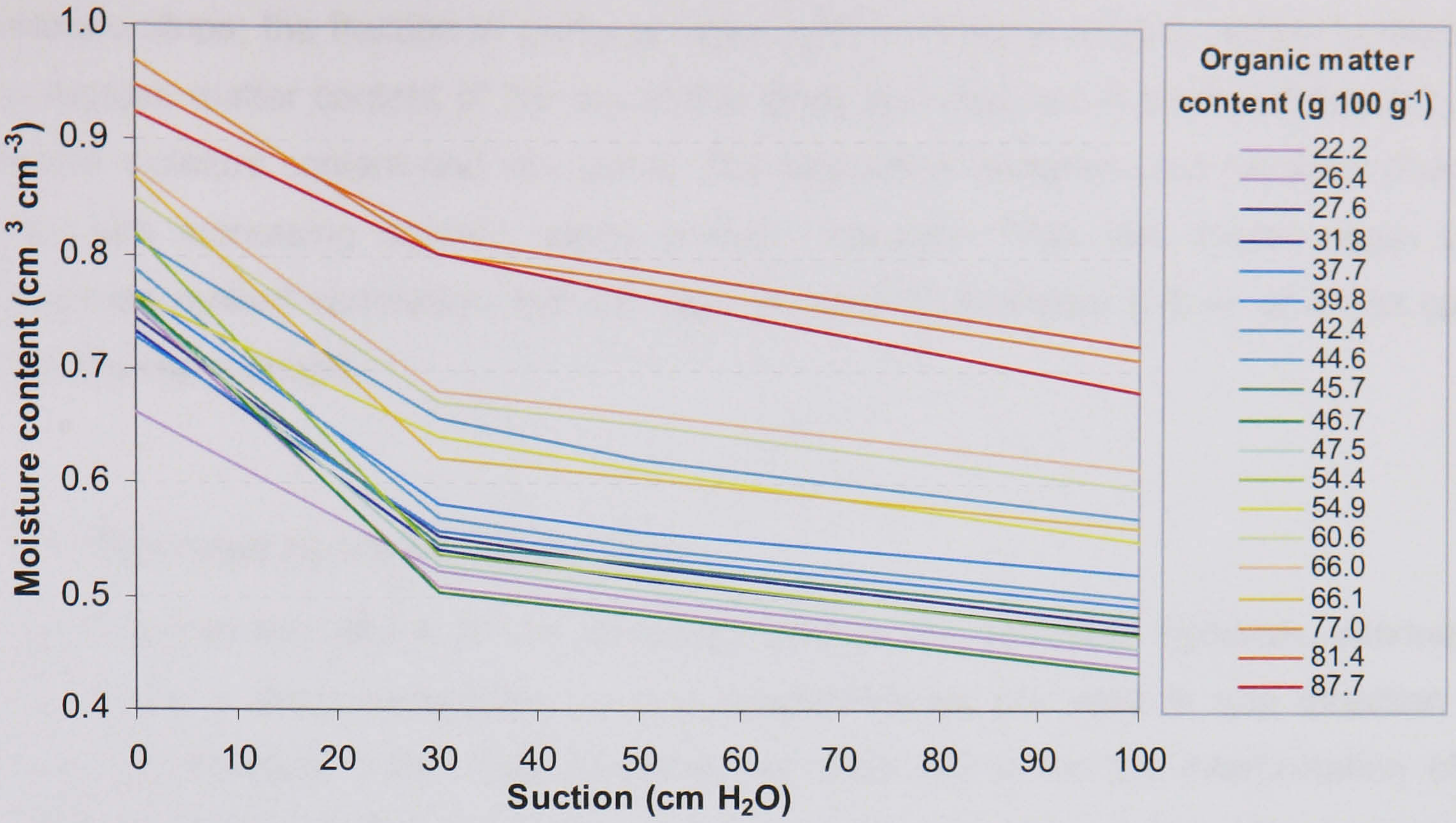


Figure 6.3: Water release curves, sorted by organic matter content.

Table 6.5: Spearman ranked correlation matrix between water release characteristics and organic matter content.

	h (cm H_2O)	om $_{0\text{-}3}$ r_s	om $_{0\text{-}3}$ *p*	om $_{4\text{-}7}$ r_s	om $_{4\text{-}7}$ *p*	om $_{12\text{-}15}$ r_s	om $_{12\text{-}15}$ *p*	om $_{16\text{-}19}$ r_s	om $_{16\text{-}19}$ *p*
$\Phi_{0\text{-}3}$	0	0.330	0.131						
$\Phi_{0\text{-}3}$	-30	-0.015	0.944						
$\Phi_{0\text{-}3}$	-50	-0.046	0.834						
$\Phi_{0\text{-}3}$	-100	-0.072	0.742						
$\Phi_{4\text{-}7}$	0			0.630	0.004				
$\Phi_{4\text{-}7}$	-30			0.484	0.027				
$\Phi_{4\text{-}7}$	-50			0.439	0.044				
$\Phi_{4\text{-}7}$	-100			0.416	0.057				
$\Phi_{12\text{-}15}$	0					0.638	0.004		
$\Phi_{12\text{-}15}$	-30					0.734	0.001		
$\Phi_{12\text{-}15}$	-50					0.740	0.001		
$\Phi_{12\text{-}15}$	-100					0.578	0.010		
$\Phi_{16\text{-}19}$	0							0.897	0.000
$\Phi_{16\text{-}19}$	-30							0.931	0.000
$\Phi_{16\text{-}19}$	-50							0.917	0.000
$\Phi_{16\text{-}19}$	-100							0.722	0.001

$n = 19$, $p < 0.05$)
Φ: porosity(cm^3 cm^{-3}), om: organic matter content (g 100 g^{-1})
Values indicated in grey are not significant

In the previous section, it became clear that organic matter content is an important factor in determining the porosity of the topsoil. As Figure 6.3 shows, not only does total porosity increase with increasing organic matter content, but this also applies to different porosity classes. Different points on the water release curves were compared to the organic matter content in Table 6.5. There is a significant positive relationship between organic matter and porosity with depth, showing that for each pore size class, indicated by the different pressure steps; the fraction of pores is larger with increasing organic matter content. So the organic matter content of the soil in the study area has an indirect positive effect on the soil moisture content and vice versa. The proportion between pore fractions does not differ with increasing organic matter content, however. This was tested again using Spearman ranked correlation, but can also be seen from Figure 6.3, in which all curves have the same shape.

6.3.5 Saturated hydraulic conductivity

The study into the effects of soil characteristics on the saturated hydraulic conductivity (K_{sat}) needs a short explanation: as K_{sat} measurements are valid in one direction only (Klute and Dirksen, 1986), this direction has implications for the interpretation of the measured values. In this case, K_{sat} was measured vertically, so the values cannot be easily related to horizontally varying variables.

Also, as was done in previous sections, variables for different depths cannot simply be averaged out to create an average over the top 20 cm. In this case, the minimum value over the depth involved should be taken because it is the minimum saturated conductivity which determines the maximum flow of water through the entire (top)soil. So, the conductivity at 10-20 cm (Section 4.4.2) also has implications on soil properties above this depth. If the conductivity at a certain depth is lower than elsewhere in the profile, this will still have implications on the soil water status and dynamics and therefore the soil properties and structure of the overlying and underlying soil horizons.

On average, saturated hydraulic conductivity values were 46.5 cm hr^{-1} in the top 10 cm of the soil, and 27.6 cm hr^{-1} between 10 and 20 cm depth (Table 6.6). Although these values appear to be relatively high, this corresponds with the high porosity values in the area. The findings are also in line with findings by other studies. Andriesse (1988) for example, reports K_{sat} values of 22 cm hr^{-1} for the top 15 cm of a peat in Ontario, USA and K_{sat} values in the range of 29 to 67 cm hr^{-1} in Florida peat soils. Laurén and Heiskanen (1997) even report extremely high K_{sat} values of up to 1200 cm hr^{-1} in low humified peats in Finland.

In the study area, the difference in K_{sat} between the two layers was significant, tested by a Kruskal-Wallis test ($p = 0.02$). However, the standard deviation was high, indicating a highly variable nature of the K_{sat}. The minimum K_{sat} measured was 4.2 cm hr^{-1}, and the maximum was 141.5 cm hr^{-1}. This maximum was only found on one location and was nearly twice as high as the next highest value (88.0 cm hr^{-1}). This was not an error in the measurement however, as the 0-10 cm and the 10-20 cm samples showed a very close similarity (141.5 *vs.* 137.2 cm hr^{-1}, resp.). Possibly, a vertical crack or large root hole could have caused this high value.

Table 6.6: Descriptive statistics for the saturated hydraulic conductivity.

	Saturated hydraulic conductivity (cm hr^{-1})	
Depth	**0-10**	**10-20**
Mean	46.5	27.6
Median	44.4	16.2
Min	4.2	1.5
Max	141.5	137.2
St. dev.	34.19	31.16
coeff. of var.	0.74	1.13
n	22	22

Analyses showed, that there was no significant correlation between the K_{sat} at 0-10 and 10-20 cm depth (n =18, due to missing data). A reason for this lack of correlation could be due to (a combination of) the large incorporated error of the measurement (Wang *et al.*, 1998) and high natural variability of K_{sat}.

K_{sat} values at 0-10 cm depth showed a significant negative correlation with mean soil moisture content (an average over all 19 occasions) of the top 20 cm (r_s = -0.48, p = 0.047). The correlation was more significant between K_{sat} and the minimum soil moisture content measured (r_s = -0.56, p = 0.021, soil moisture data of the 28th of July, 1999). This reflected the increased drainage with increasing saturated hydraulic conductivity. Also, a negative correlation with the topographic index was distinguished. The relationship between slope angle and K_{sat} was not statistically significant.

No significant correlations could be found between K_{sat}, organic matter content and the total porosity. This can be explained by the fact that both the these variables were taken with only two samples of 3 cm in thickness, leaving another 4 cm unsampled, whereas the hydraulic conductivity is dependent on the *minimum* of these variables.

Table 6.7: Spearman ranked correlation between volume of transmission pores and K_{sat}.

Transmission pores (%)	$K_{sat, 0-10}$		$K_{sat, 0-20}$	
Depth (cm)	r_s	p	r_s	p
0-3	0.53	0.014		
4-7	-0.06	0.778		
Minimum of 0-3 and 4-7	0.32	0.165		
12-15			0.50	0.029
16-19			0.31	0.181
Minimum of 12-15 and 16-19			0.47	0.047

In most cases, the volume of transmission pores (Section 6.3.2) showed a significant positive correlation with the saturated hydraulic conductivity (Table 6.7). One of the sample points was removed from the analysis, because extraordinary high values were found at both depths and were regarded as outliers (see above). K_{sat} values were directly compared with the transmission pore volume at certain depths, but also with the minimum porosity found within the range of the K_{sat} measurement.

The K_{sat} at 10-20 cm depth does show a significant positive correlation with slope (r_s = 0.40, p = 0.0996), but also a negative correlation with the maximum soil moisture measured (r_s = -0.47, p = 0.055, on 2^{nd} of November 1998). This was logical, as the higher the saturated conductivity, the quicker the soil drains, resulting in lower soil moisture contents.

The correlation between K_{sat} and organic matter content was significant with 90% confidence limits (r_s = 0.42, p = 0.080). This can be explained by the fact that organic matter generally has on the soil structure (White, 1997), by making it more open and aerated. It therefore also increases the porosity. Although the $p > 0.10$ is not conventionally taken as significance level, the level was chosen because of the relatively low number of samples and the complex and subtle relationship between K_{sat} and organic matter content.

6.4 Spatial soil moisture variability

Objective 2 of the hydrological processes (Section 1.2) aims to relate soil moisture organisation to topography, soil physical characteristics and vegetation. In order to achieve this objective, this section is structured as follows:

- In Section 6.4.1, the general descriptive statistics of the soil moisture measurements are presented. The section also describes the soil moisture variability in relation the different soil profiles within the main TDR-grid.
- Section 6.4.2 relates soil moisture to the topography within the TDR-grid.
- Section 6.4.3 presents the spatial variability of soil moisture.
- Section 6.4.4 describes the variability of soil moisture across the entire hillslope, in order to assess how representative the TDR-grid is to the hillslope scale.
- In the final Section 6.4.5, results are presented of the soil moisture readings within an area with higher grazing pressures and are consequently compared to the results from the main TDR-grid.

6.4.1 Soil moisture variability in relation to the soil profile

TDR-grid measurements (Table 6.8) covered a wide range of different soil moisture conditions, from an average hillslope soil moisture content of 0.36 (28-07-1999) to 0.66 $cm^3\ cm^{-3}$ (02-11-1998). Individual point values within the TDR-grid ranged from 0.15 to more than 0.90 $cm^3\ cm^{-3}$, which is not unusual for peat soils (*e.g.* Pepin *et al.*, 1992; Roth *et al.*, 1992). At low average soil moisture contents, the coefficient of variance tended to be slightly higher than in wetter conditions, suggesting that the soil moisture distribution becomes more heterogeneous with decreasing soil moisture (Figure 6.4).

Table 6.8: Descriptive statistics of the soil moisture measurements, sorted by mean soil moisture.

date	mean ($cm^3\ cm^{-3}$)	min ($cm^3\ cm^{-3}$)	max ($cm^3\ cm^{-3}$)	Q_1 ($cm^3\ cm^{-3}$)	Q_3 ($cm^3\ cm^{-3}$)	s. d. ($cm^3\ cm^{-3}$)	c. of var (-)	N (-)
28/07/99	0.355	0.157	0.674	0.311	0.399	0.084	0.237	123
22/06/99	0.477	0.274	0.764	0.422	0.523	0.077	0.161	121
09/10/98	0.550	0.348	0.869	0.505	0.587	0.076	0.138	96
18/03/99	0.553	0.376	0.792	0.529	0.575	0.059	0.107	151
12/10/98	0.566	0.389	0.859	0.534	0.586	0.061	0.108	143
17/02/99	0.569	0.396	0.808	0.546	0.589	0.053	0.093	151
04/02/99	0.572	0.402	0.869	0.540	0.586	0.063	0.110	140
25/10/99	0.572	0.461	0.679	0.549	0.600	0.044	0.077	71
30/11/98	0.586	0.422	0.824	0.558	0.608	0.056	0.096	150
17/12/98	0.591	0.416	0.859	0.563	0.607	0.060	0.102	150
23/11/98	0.594	0.416	0.841	0.575	0.608	0.057	0.096	150
19/10/98	0.594	0.429	0.841	0.563	0.630	0.059	0.099	151
12/04/99	0.601	0.448	0.878	0.569	0.624	0.056	0.093	149
14/10/98	0.614	0.422	0.816	0.586	0.638	0.054	0.088	143
21/01/99	0.624	0.448	0.970	0.586	0.654	0.070	0.112	151
09/11/98	0.639	0.517	0.933	0.597	0.668	0.060	0.094	150
26/10/98	0.641	0.442	0.859	0.597	0.672	0.061	0.095	150
05/01/99	0.645	0.498	0.921	0.603	0.663	0.060	0.093	150
02/11/98	0.655	0.474	0.977	0.603	0.685	0.074	0.113	149

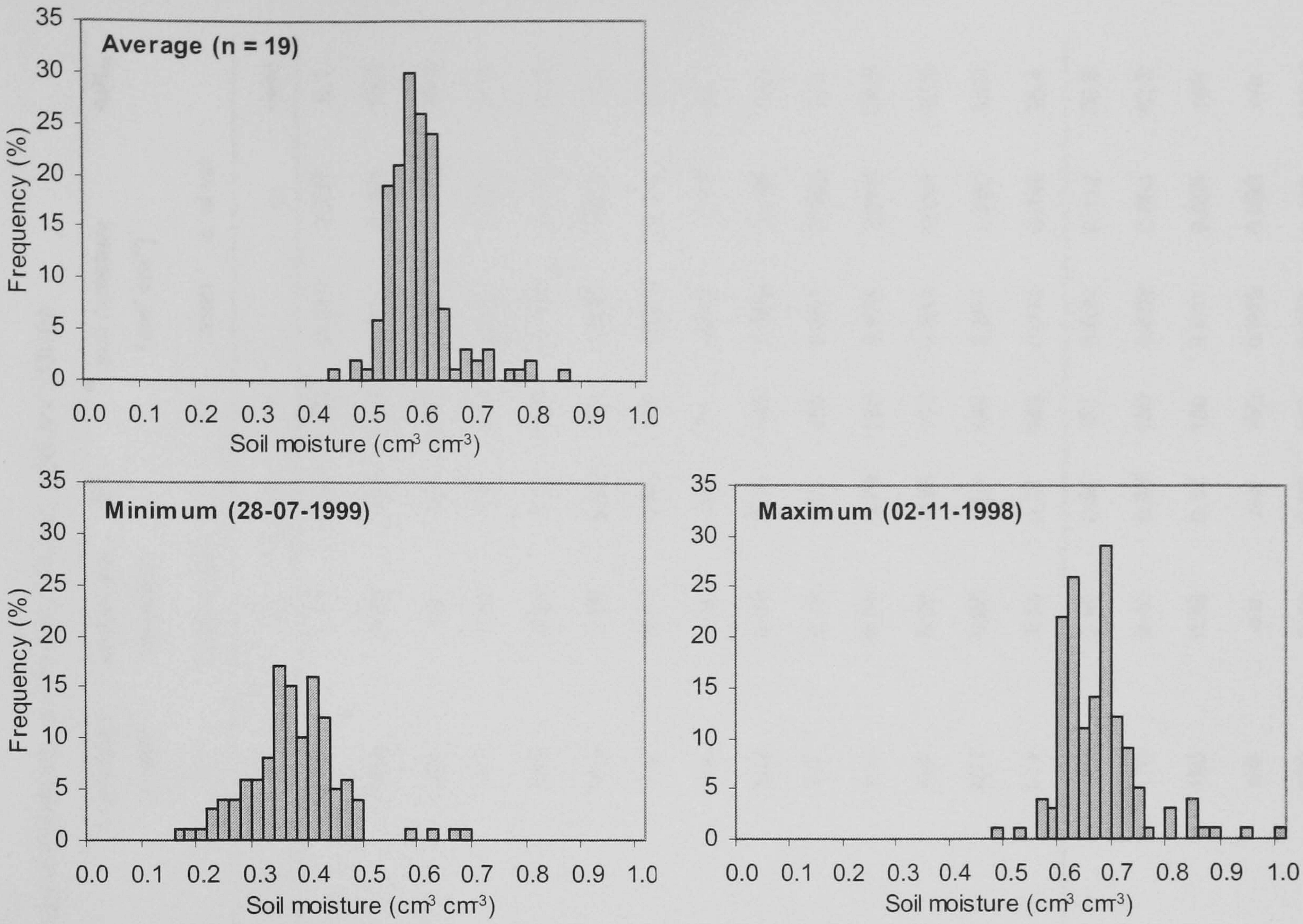


Figure 6.4: Histograms of soil moisture distribution: average (n = 19), minimum (28-07-1999) and maximum (02-11-1998).

6.4.2 Spatial soil moisture organisation in relation to topography

In general, soil moisture values show a tendency to be highest in the flat areas adjacent to the stream and lowest in the area with the steepest slope (up to 18°). Soil moisture contents on the hillslope averaged over all occasions show a significant ($p = 0.001$) but weak ($r_s = -0.27$, $n = 151$) negative ranked correlation (Spearman rank correlation coefficient, r_s) with slope, indicating increased lateral drainage on the steeper sections. A significant positive but also weak correlation with topographic index ($r_s = 0.21$, $p = 0.009$) could be distinguished, showing higher soil moisture levels in low sloping areas and/or parts with large contributing areas, as reported elsewhere (Kirkby, 1975; Quinn *et al.*, 1995).

6.4.3 Geostatistical analysis of soil moisture variability within the TDR-grid

Using the TDR grid data, semivariograms (Section 4.3.6) were calculated for all different data sets. The results are shown in Table 6.9.

Table 6.9: Descriptive statistics and geostatistical results of the soil moisture measurements, sorted by mean soil moisture

	date	stream state	model	lag interv	active distance	nugget	sill	correlation length	explained variation	R^2	soil moisture ($cm^3\ cm^{-3}$)			API_{18}
						C_0	$C_0 + C$	A_0	$C/(C_0 + C)$		N	mean	c. of var	
				(m)	(m)	($\times 10^{-4}$ ($cm^3\ cm^{-3})^2$)	($\times 10^{-4}$ ($cm^3\ cm^{-3})^2$)	(m)	(-)	(-)	(-)		(-)	(mm)
'dry' preferred state	28-7-1999	Baseflow	Spher.	10	60	16.1	55.9	16.6	0.71	0.67	123	0.355	0.237	6.1
	22-6-1999	Baseflow	Spher.	10	60	13.6	48.9	16.8	0.72	0.85	121	0.477	0.161	10.3
	9-10-1998	Baseflow	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	96	0.55	0.138	30.0
	18-3-1999	Baseflow	Spher.	10	70	6.2	28.9	16.7	0.78	0.7	151	0.553	0.107	17.8
	12-10-1998	Baseflow	Spher.	9	100	6.9	28.5	14.9	0.76	0.74	143	0.566	0.108	30.4
	17-2-1999	Baseflow	Spher.	10	60	5.0	23.1	14.6	0.78	0.48	151	0.569	0.093	*n/a*
	4-2-1999	Baseflow	Exp.	9	100	8.9	31.0	7.9	0.71	0.85	140	0.572	0.110	26.6
	25-10-1999	Baseflow	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	71	0.572	0.077	47.1
	30-11-1998	*n/a*	Spher.	10	70	5.7	25.4	16.7	0.78	0.75	150	0.586	0.096	*n/a*
	17-12-1998	Baseflow	Exp.	9	100	7.3	28.0	7.7	0.78	0.75	150	0.591	0.102	*n/a*
	23-11-1998	Baseflow	Exp.	9	60	7.9	26.2	4.6	0.70	0.70	150	0.594	0.096	29.3
	19-10-1998	Baseflow	Exp.	9	90	9.0	28.7	5.0	0.69	0.89	151	0.594	0.099	48.5
	12-4-1999	Inflection	Spher.	9	70	4.4	25.3	15.7	0.83	0.64	149	0.601	0.093	43.8
	14-10-1998	Baseflow	Spher.	9	75	5.6	24.8	14.6	0.78	0.77	143	0.614	0.088	35.4
'wet' preferred state	21-1-1999	Baseflow	Spher.	9	210	27.0	50.0	180	0.46	0.90	151	0.624	0.112	70.5
	9-11-1998	Recession	Spher.	9	210	21.0	35.0	170	0.40	0.88	150	0.639	0.094	92.2
	26-10-1998	Recession	Exp.	20	230	24.5	39.5	150	0.38	0.97	150	0.641	0.095	109
	5-1-1999	Recession	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	150	0.645	0.093	*n/a*
	2-11-1998	Rising	Spher.	18	200	25.8	55.1	180	0.53	0.98	149	0.655	0.113	112.4

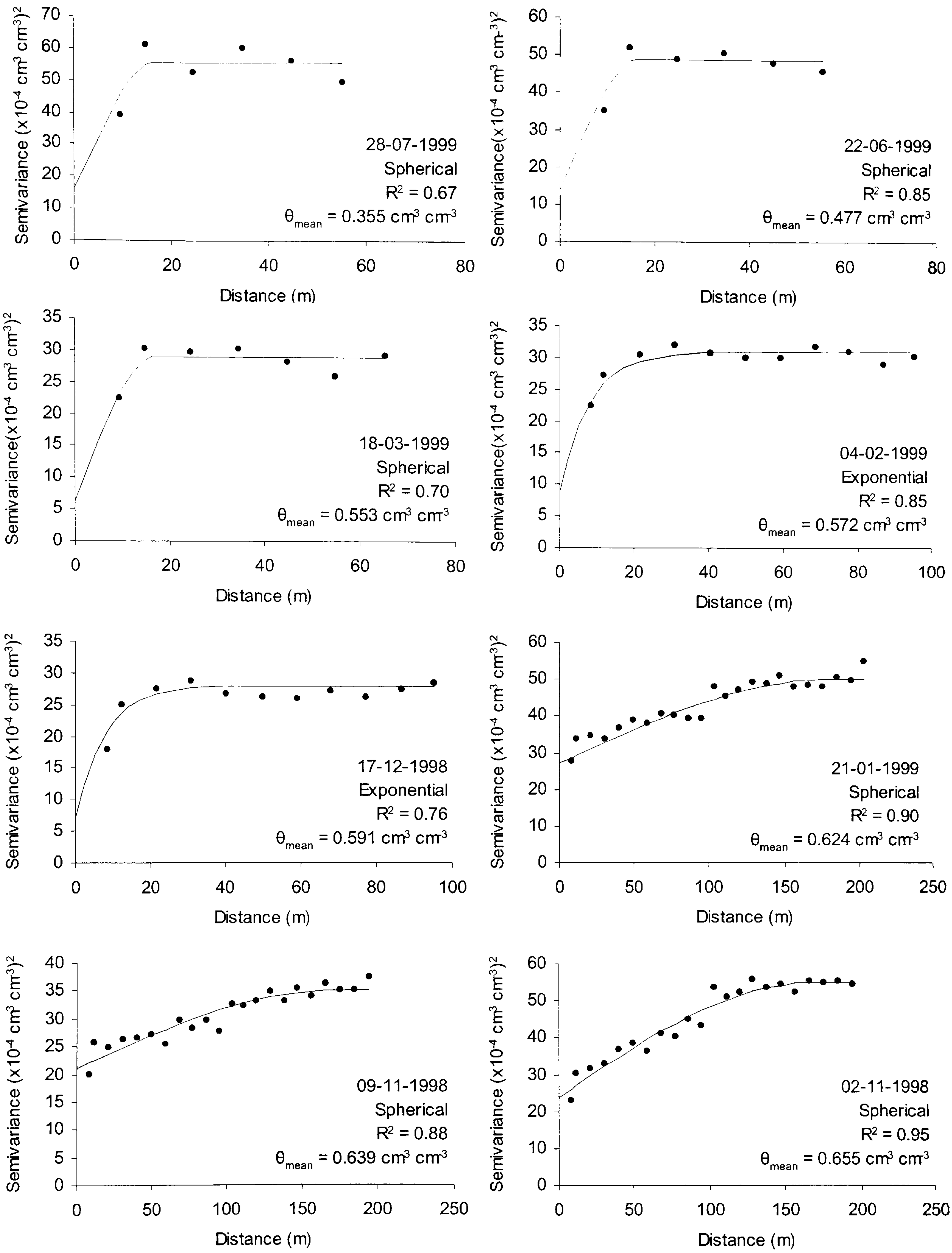


Figure 6.5: Semivariograms of the TDR-grid (n = 151) in different wetness states.

Nearly all data sets were modelled using a lag interval of 10 m at first, because of the TDR measuring interval. Due to this sampling interval, results were optimal for this lag distance. The R^2-values for the curve fitting ranged from 0.48 to 0.90, showing the reasonable fit in most cases. Figure 6.5 shows eight selected fitted semivariograms in order of increasing soil moisture.

As the nugget is the non-spatial variation within a semivariogram, and the sill denotes the spatial variation, the ratio between sill and nugget is a measure of the amount of explained variation (Webster and Oliver, 1990). Average values were around 0.70, with a minimum of 0.38 and a maximum of 0.83, suggesting a good explanation in general at short distance. For 16 datasets, curves were fitted to the semivariograms. The other three showed a pure nugget effect and were left out of the analysis.

Curve fitting of the different semivariograms demonstrated a distinct difference between 'dry' and 'wet' conditions in terms of active distance and range. The terms 'dry' and 'wet' are used in the sense described by Grayson *et al.* (1997). In 'dry' conditions, arbitrarily defined as below a volumetric soil moisture content of about 0.60 cm^3 cm^{-3}, the active distance over which the model could be fitted was relatively short, ranging between 60 and 100 m. This active distance is the distance over which the semivariogram could be modelled (Webster and Oliver, 1990). The semivariograms showed a short range in 'dry' conditions, close to the sampling distance of 10 m (Table 6.9). The majority of the semivariograms could be fitted with a spherical model, the remainder by an exponential model.

As the range (or correlation length, Western *et al.*, 1998) of the spherical and exponential models was established in a very different way (Webster and Oliver, 1990), strictly they are not directly comparable because there is no limit to the spatial dependence with an exponential model. As a rule of thumb, however, a limit of three times the calculated range ($3 \times A_0$) can be taken as the 'effective' range, which is the point at which 95% of the value of the sill has been reached (Webster and Oliver, 1990). So although the exponential models in the table seem to show a shorter range than spherical models, values are comparable. The (effective) range therefore varied between 13.8 and 23.7 m.

In the driest situation (28th July 1999), with an average soil moisture content of 0.36 cm^3 cm^{-3}, the model fit was relatively poor (Fig. 6.5), probably due to a spatial scale smaller than the separation distance between the different soil moisture points.

During conditions with an average hillslope soil moisture content between 0.61 and 0.67 cm^3 cm^{-3} (the 'wet' situation), spherical models fitted the semivariograms appropriately as well, but with a longer range of more than 150 m in general. Active distances were also longer, between 200 and 230 m.

In order to analyse the striking difference between the 'dry' and 'wet' states in more detail, the models were used to krig (geostatistical interpolation; Section 4.3.6) soil moisture of the area covered by the grid. Due to the short range in 'dry' conditions, the plots showed very heterogeneous soil moisture patterns with largely unconnected wet and dry areas

(Fig. 6.6). Kriged plots of ´wet´ conditions showed a much more homogeneous pattern with large interconnected wet areas. These findings are similar to results published by Grayson *et al.* (1997) and Western *et al.* (1999) in temperate Australia and the ´wet´ and ´dry´ preferred states as defined by Grayson *et al.* (1997; Section 2.6).

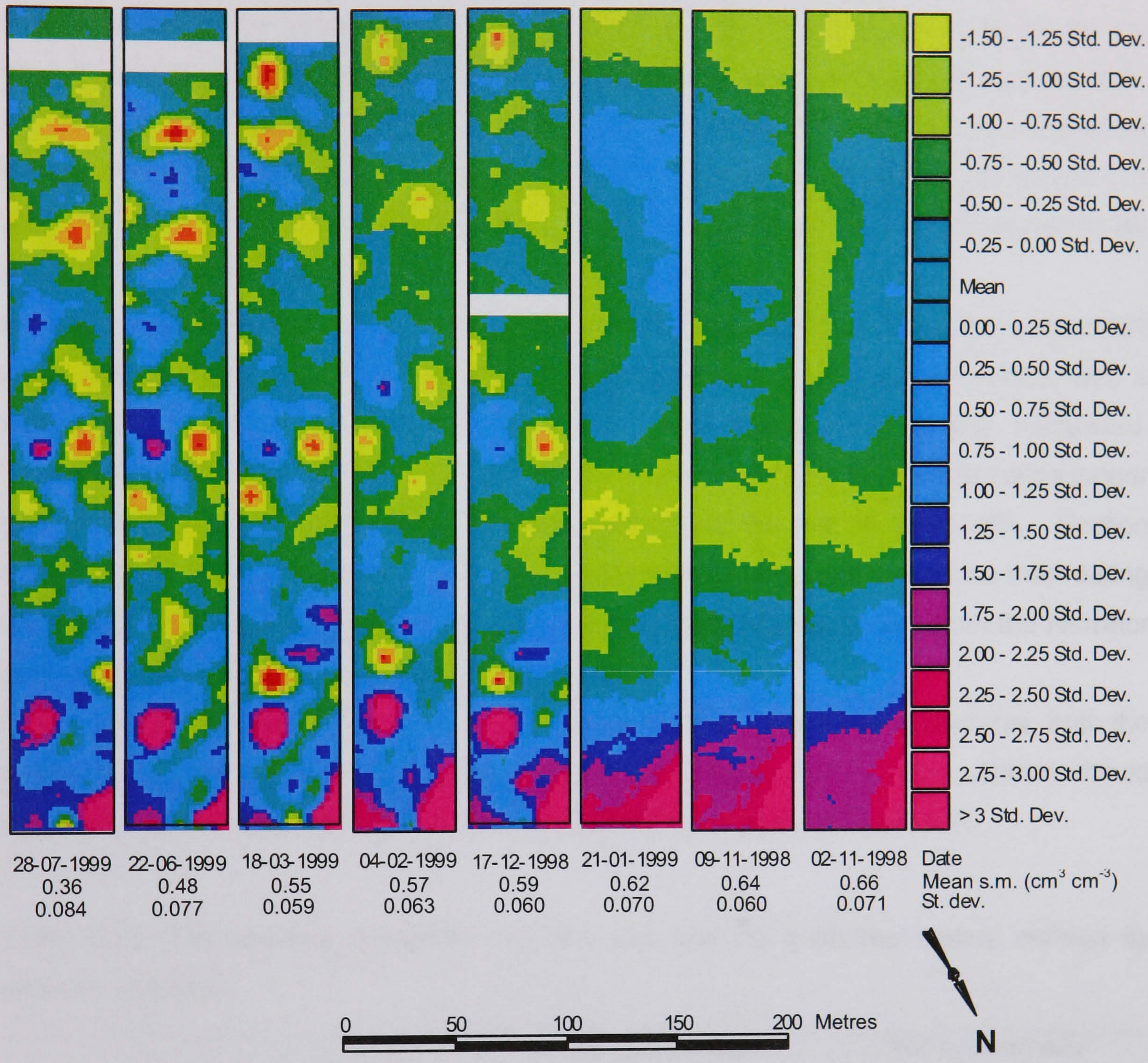


Figure 6.6: Kriged soil moisture plots. The plots cover the hillslope TDR-grid from the top to the foot of the slope.

The apparently sharp distinction between states, defined above by an average soil moisture content of 0.60 cm^3 cm^{-3} may not be the only or the most appropriate measure to separate the different wetness states. Especially when values are compared to a different area within the catchment, soil conditions might be different, yielding a different average soil moisture value. Therefore, additional variables were chosen to define the wetness threshold.

It has been shown that the (effective) range or correlation length from the geostatistical analysis (Table 6.9) showed a distinctively larger value in the wet preferred state than in the dry state. During dry conditions, the value is generally less than 24 m, whereas in wet conditions, this amounts to more than 100 m. Similarly, the active distance could be taken, closely related to the range. Within the hillslope TDR grid, the active distance for the dry state is typically equal or less than 100 m. In wet conditions, this distance is around 200 - 250 m. The correlation length is only dependent on the spatial variability and is therefore independent of the measured soil moisture values, enabling the usage of this length at a different location. However, the correlation length and active distance is still related to the size and the spacing between individual samples of the grid.
Another option measure to separate the different wetness states is to use the antecedent precipitation index (API), which indicates the precipitation over a certain period, with a weight depending on the time between rainfall and the moment in time calculated. Precipitation within the last 24 hours will have a higher weighting than precipitation longer ago. Within the study area, the index is calculated over the last 18 days (API_{18}, Section 4.4.5). Table 6.9 shows that the API_{18} was much higher during wet conditions than during dry conditions. The API_{18} used in this table was calculated by using data from the Narrator data set however, slightly decreasing the validity.
It can therefore be concluded, that in order to define the different wetness states, both the range (and/or the active distance), the API and the average soil moisture content should be taken. Definitions for the TDR grid on the hillslope are given in Table 6.10.

Table 6.10: The wetness threshold between wet and dry preferred states, defined by different variables.

	'Dry' preferred state	**'Wet' preferred state**
Average hillslope soil moisture content (cm^3 cm^{-3})	0.36 – 0.60	0.60 – 0.66
Correlation length (m)	< 25	> 150
Active distance (m)	< 100	> 200
Antecedent precipitation index (API, mm)	< 50	> 70

6.4.4 Representativity of the TDR grid in relation to the hillslope scale

In order to investigate how representative the TDR grid was to the hillslope scale, soil moisture was measured across the entire hillslope on a 10×10 m grid, covering 1977 points (Section 4.3.4). A geostatistical approach was adopted to compare the spatial distribution of soil moisture of the main TDR grid to the hillslope distribution. When kriged and mapped on a 2.5 m grid size plot in a GIS, a clear effect of the walking direction of the groups could be distinguished. As this direction (due north) does not coincide with the slope aspect, it could clearly be identified (Fig. 6.7). The difference between groups was therefore first eliminated.

Table 6.11: Descriptive statistics and Mann-Whitney test for the six groups.

Group	N	θ_{min} cm^3 cm^{-3}	θ_{max} cm^3 cm^{-3}	$\theta_{average}$ cm^3 cm^{-3}	St. dev.	A	B	C	D	E	Other groups
A	301	0.405	0.790	0.688	0.063						0.886
B	330	0.310	0.783	0.665	0.071	0.000					0.000
C	343	0.409	0.769	0.646	0.047	0.000	0.000				0.000
D	341	0.534	0.801	0.745	0.032	0.000	0.000	0.000			0.000
E	333	0.329	0.872	0.684	0.078	0.880	0.000	0.000	0.000		0.640
F	296	0.478	0.787	0.699	0.060	0.012	0.000	0.000	0.000	0.018	0.001

The differences in mean between groups were analysed by using the Mann-Whitney test (non-parametric data). Each single line was compared with the other five lines within the same set. This was done as well as comparing the total group means. Most variation was expected to be attributed to a different way of inserting the probes into the soil, as the difference in calibration between probes established and removed in the laboratory (Section 4.3.3).

With the exception of groups A and E, the Mann-Whitney test showed that the means of the groups are significantly different within a 95% confidence interval (Table 6.11). The last column of the table shows the results when the groups are compared with the combination of all other groups.

Table 6.12: The different geostatistical exponential models used in the analysis.

dataset	stream state	lag interval	active distance	nugget	sill	range	explained variation	R^2	soil moisture		
				C_0	$C_0 + C$	A_0	$C/(C_0 + C)$		N	mean	s. d.
		(m)	(m)	(× 10^{-4} (cm^3 cm^{-3})^2)	(× 10^{-4} (cm^3 cm^{-3})^2)	(m)	(m)	(-)	(-)	(cm^3 cm^{-3})	(cm^3 cm^{-3})
Uncorr.	Baseflow	10	100	13.0	42.0	19.5	0.76	0.89	1977	*0.68	0.059
Corr.	Baseflow	10	100	9.5	31.2	11.0	0.70	0.81	1977	*0.68	0.059

**This average is taken from the thetaprobe measurements and is, due to the difference in depth and method, not directly comparable to the TDR measurements. The equivalent TDR average is around 0.57cm^3 cm^{-3} and reflects the dry state.*

These results were used for correcting the data. Where the difference in mean was significantly different to the mean of the other groups together, on a 95% confidence level, a correction was carried out. This was done by calculating the difference in means and all individual soil moisture readings were corrected by adding or subtracting the difference. With this data set, a new geostatistical analysis was carried out. With the corrected data set, and exponential model could be identified with a very short range of 11 m, close to the sampling distance of 10 m (Table 6.12).

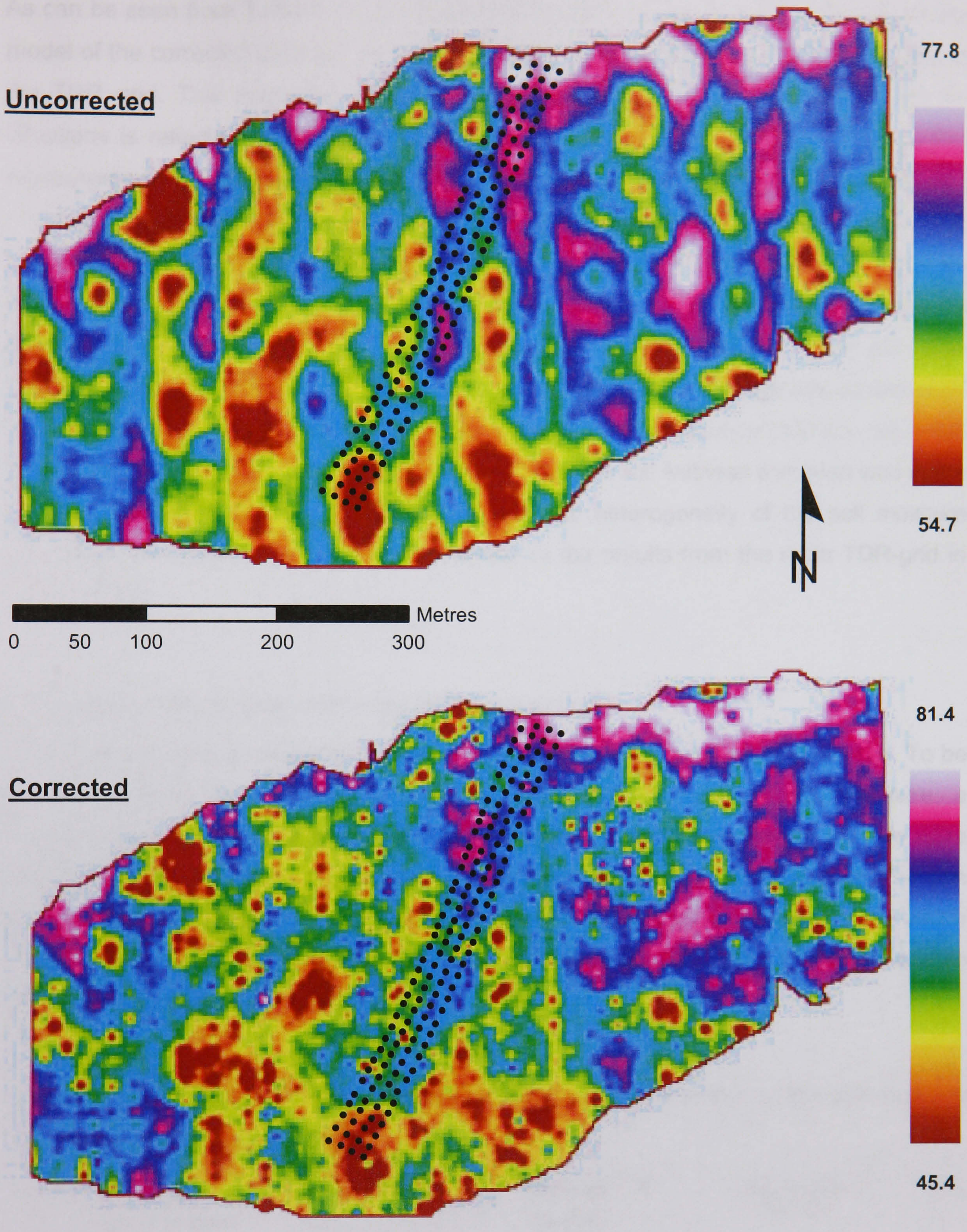


Figure 6.7: Kriged soil moisture plots of the hillslope experiment. Soil moisture values are in per cent by volume.

As can be seen from Table 6.12, the explained variation is around 70%. The exponential model of the corrected data set shows a very similar short-range effect as the dry state of the TDR grid. This suggests, that the heterogeneous pattern of the TDR grid in dry situations is reflected in the pattern across the hillslope. As described in Section 4.3.4, measurements across the hillslope were carried out after a dry spell of more than a week. However, the average soil moisture content using the thetaprobe was found to be 0.68 cm^3 cm^{-3}. This average is not directly comparable to the TDR measurements due to the difference in depth and method. The overall soil moisture for the grid was therefore determined from the stream discharge, a measure for the wetness of the soil (also described in Section 6.6). It was shown that the equivalent TDR average was around 0.57 cm^3 cm^{-3} and therefore reflects the dry state. Also, the active distance (100 m), the range (A_0 = 11.0 m) and the API_{18} (21.1 mm) indicated that the soil wetness condition was in the dry state. It could therefore be concluded, that the heterogeneity of the soil moisture mosaic on the whole hillslope was comparable to the results from the main TDR-grid in the dry state.

6.4.5 Soil moisture measurements in the grazing grid

The main TDR-grid as described above was located in a relatively low grazed area. To be able to compare soil moisture conditions in areas with a higher grazing pressure, a smaller grid was established on the same hillslope on a location where animals were frequently observed and with a vegetation type reflecting a high grazing intensity (Section 4.3.5 Chapter 7). Measurements were carried out on four separate occasions, one which coincided with measurements over the hillslope TDR grid (25th October 1999) to enable descriptive statistics to be compared.

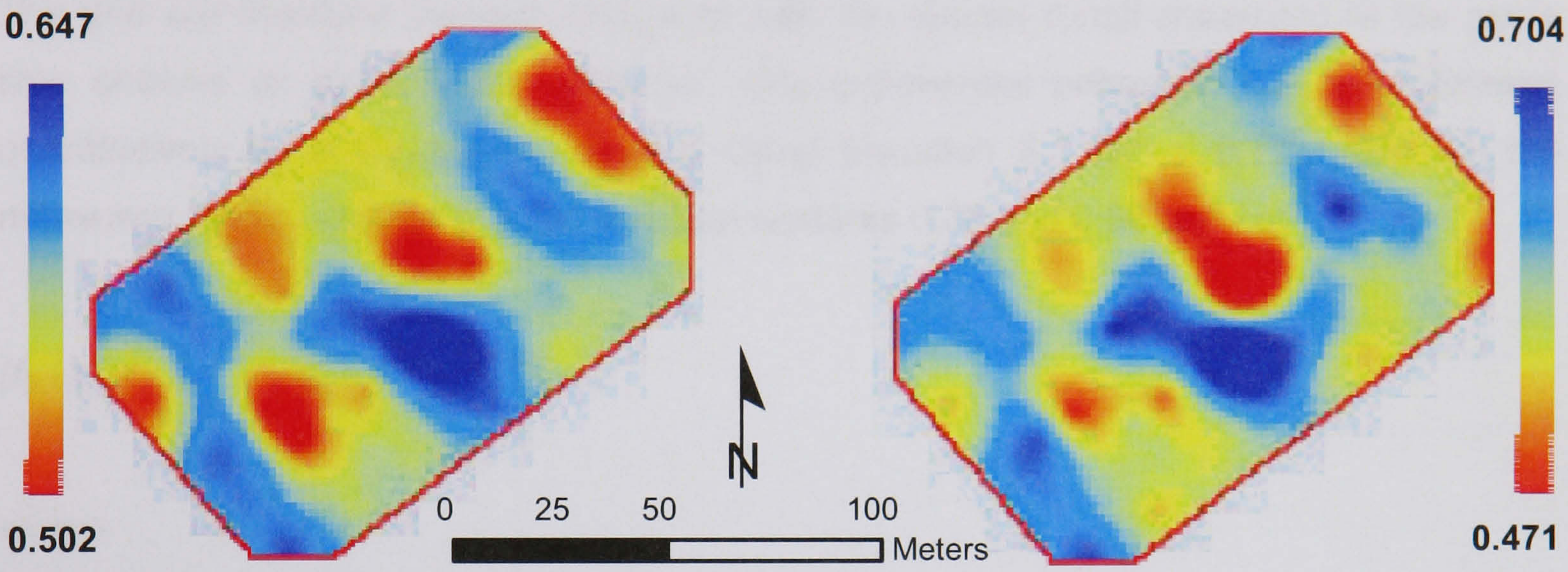
Table 6.13: Descriptive statistics and geostatistical spherical models of the soil moisture measurements in the grazing grid.

Date	lag interval	active distance	nugget	sill	range	explained variation	R^2	soil moisture (vol. %)			API_{18}
			C_0	$C_0 + C$	A_0	$C/(C_0 + C)$		N	mean	s. d.	
	(m)	(m)	($\times 10^{-4}$ (cm^3 $cm^{-3})^2$)	($\times 10^{-4}$ (cm^3 $cm^{-3})^2$)	(m)	(m)	(-)	(-)	(cm^3 cm^{-3})	(cm^3 cm^{-3})	(mm)
15/11/99	9	40	5.35	19.2	25.3	0.72	0.99	63	0.563	0.040	19.1
02/12/99	10	50	0.97	12.8	22.2	0.92	0.94	66	0.576	0.034	60.4*
25/10/99	9	50	0.01	15.7	19.4	0.99	0.88	66	0.587	0.038	47.1
26/11/99	9	40	0.01	17.5	24.4	0.99	0.93	65	0.589	0.037	38.1*
Main TDR grid:											
25/10/99	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	71	0.572	0.044	47.1

**API_{18} values are obtained from the Venford dataset and are therefore only an indication of the API_{18} in the study area.*

The soil moisture values measurements covered a relatively narrow range, with average values from 0.56 to 0.59 $cm^3\ cm^{-3}$ (Table 6.13). The measurements in both grids were comparable in terms of mean and standard deviation on the 25th October 1999.

Geostatistical analysis showed that semivariograms could be fitted with model variable values similar to those in the main TDR-grid. Figure 6.8 shows soil moisture plots, obtained from kriged soil moisture values from the grazing grid.



15-11-1999
Mean soil moisture = 0.563 $cm^3\ cm^{-3}$

26-11-1999
Mean soil moisture = 0.589 $cm^3\ cm^{-3}$

Figure 6.8: Kriged soil moisture plots of the grazing grid.

The data suggested that all measurements were carried out in the dry preferred state. On all of the four occasions, average soil moisture values were just below the wetness threshold (Table 6.13) in comparison to the main TDR-grid. However, caution should be taken when applying the same moisture threshold to another area. Comparing the API_{18} values to the wetness threshold definition (Section 6.4.3), it was shown that in three occasions, the area was in the dry preferred state. Although the API_{18} on the 2nd December 1999 was around 60, this was not fully comparable to the API threshold, as data of the Venford data set was used, which generally shows higher API_{18} values than the Narrator dataset. Additionally, the correlation length within the grazing grid was near the upper limit of the dry preferred state, but definitely not in the range of the wet state. It can be concluded therefore, that on the basis of the definition of the wetness threshold (Section 6.1.3) all four occasions were in the dry preferred state. They do however give a good reflection of the average soil moisture conditions in the main TDR-grid and are therefore assumed to be comparable to soil moisture readings on the hillslope TDR-grid.

6.5 Temporal variability: soil moisture as antecedent wetness indicator

For each of the TDR results, the stream discharge was recorded and averaged out over the time period the soil moisture measurements were taken. In general, these measurements were completed in a time period of between two and four hours (Section 4.3.3), mostly during time periods in which stream discharges were at baseflow (indicated in Table 6.9). Average soil moisture values for the main TDR-grid were calculated for each occasion and plotted against the stream discharge (Fig. 6.9).

The grid soil moisture average compared with the stream runoff measured at the same time showed an exponential behaviour. This exponential behaviour can be estimated quantitatively by a regression analysis using Equation 6.1 (R^2 = 0.77), valid for the measured range between the soil moisture contents 0.36 and 0.66 $cm^3\ cm^{-3}$.

[6.1] $$Q = a * e^{(\frac{\theta_{average}}{b})} + c$$

where:

Q = discharge ($l\ s^{-1}$);

$\theta_{average}$ = average hillslope soil moisture content ($cm^3\ cm^{-3}$).

a, *b*, *c* are constants where:

$a = 2.3 * 10^{-4}$;

$b = 0.0496$;

$c = 2.12$.

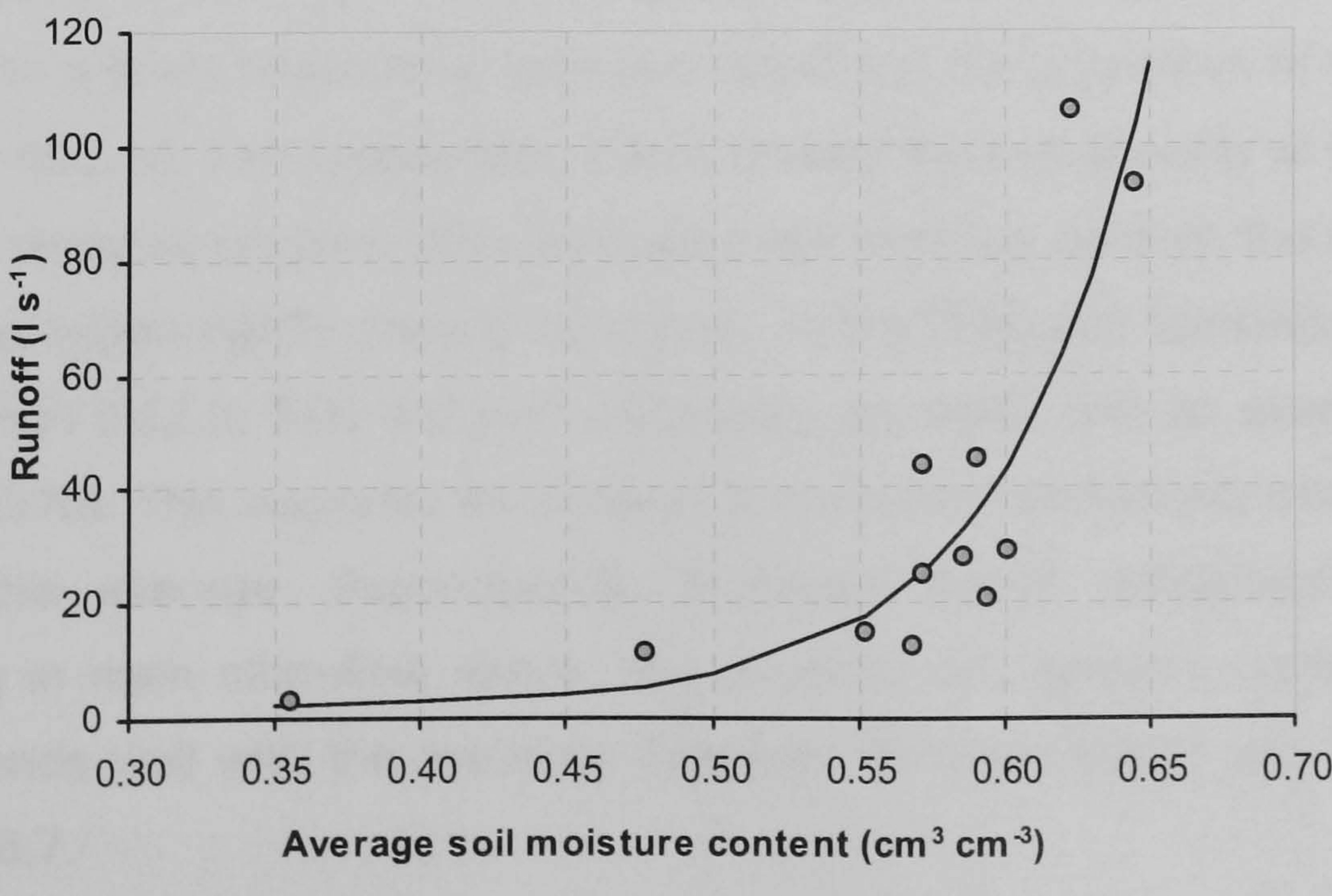


Figure 6.9: Stream discharge as function of soil moisture content.

Fig. 6.9 can be split into three sections: a dry segment, in which stream runoff slowly increases with increasing soil moisture, a transition zone, and a wet segment, with a rapid increase in runoff corresponding to a relatively small increase in average soil moisture. An average soil moisture content of 0.55 - 0.60 $cm^3\ cm^{-3}$ denotes the transition zone between the two sections. Although no occasions above 0.66 $cm^3\ cm^{-3}$ were measured, it is known from the water release characteristics (Figure 6.10) that this value does not represent saturated conditions, with typical total porosity values of around 0.80 $cm^3\ cm^{-3}$, over the top 20 cm of the soil.

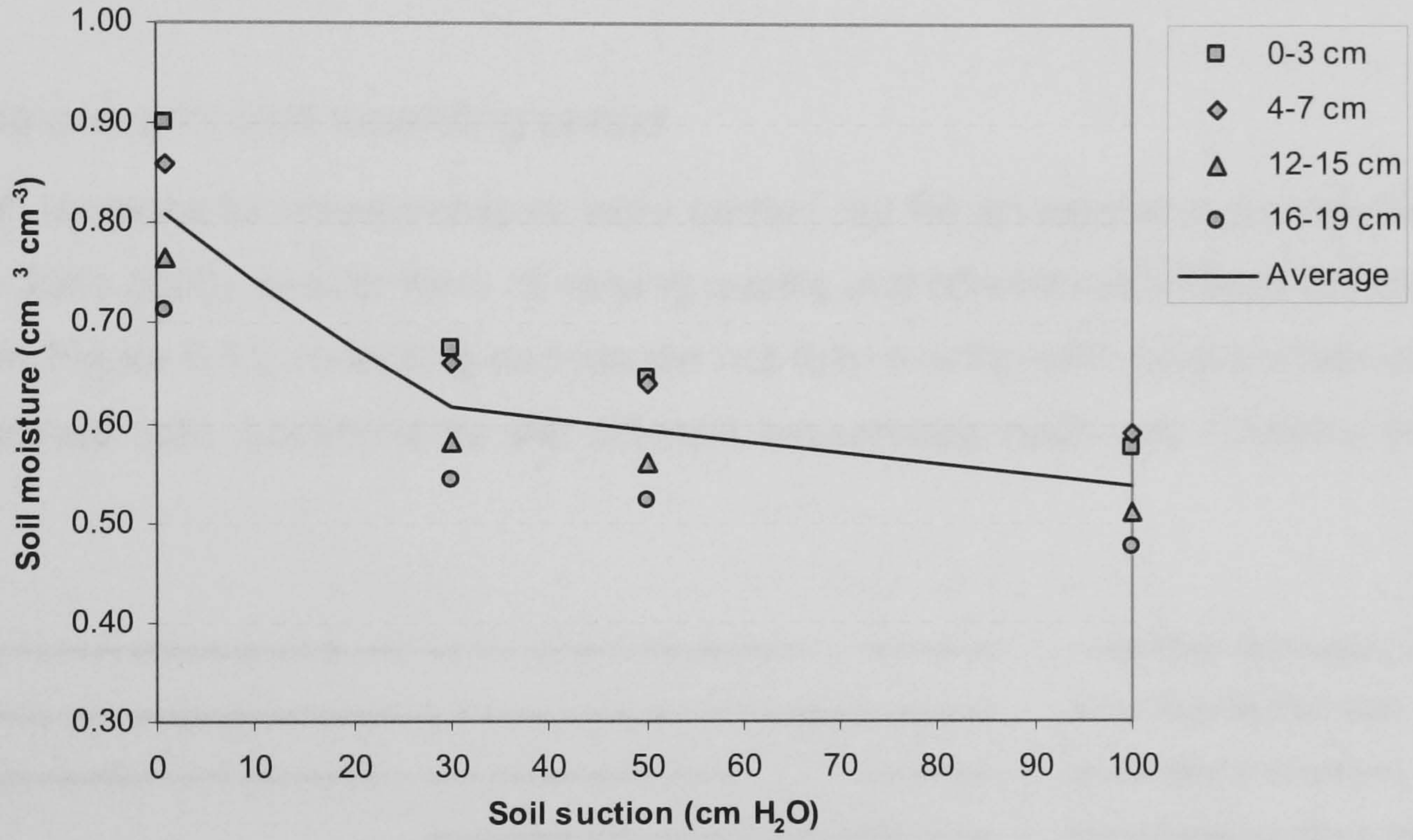


Figure 6.10: Soil water release curve, averaged over the top 20 cm on all measured locations (23) within the TDR-grid.

Deeks (pers. comm., 2001) found a similar response in a Scottish headwater catchment. She noted a good relationship between runoff and the proportion of water in transmission pores (> 50 μm). Van Genuchten (1980) showed the non-linearity of hydraulic conductivity with soil moisture content. With increasing soil moisture content, the hydraulic conductivity increases exponentially close to saturation. In the TDR-grid, transmission pores start filling up between 0.52 to 0.64 $cm^3\ cm^{-3}$ depending on depth, with an average of 0.59 $cm^3\ cm^{-3}$ (Figure 6.10). This suggests an increase in hydraulic conductivity when soil moisture rises above this average. Subsequently, increased lateral subsurface flow is generated, resulting in risen stormflow levels. The average soil moisture content of 0.59 $cm^3\ cm^{-3}$ corresponds well with the 'wetness threshold' (Section 6.4.3) and is explored further in Section 6.7.

6.6 Soil water tension at the point scale

In Section 6.3.1 it was shown that soil formation and current soil conditions in the area were typified by shallow subsurface water. As it could be expected that management factors would also have its influence close to the soil surface, the importance of shallow soil water in relation to the subsoil needed to be explored. Within the TDR grid, several tensiometer nests were installed in order to study the soil water tension within the profile through time (Section 4.5). The results were then compared to the findings across the hillslope, and are described in this section.

6.6.1 Data quality and recording period

Although tensiometer measurements were carried out for an extensive period (November 1999 to June 2000), results were of varying quality and sometimes difficult to interpret. As shown in Figure 6.11, recording periods did not fully overlap with long periods of missing or inaccurate data. Locations for the different tensiometer nests are indicated in Section 4.5.1.

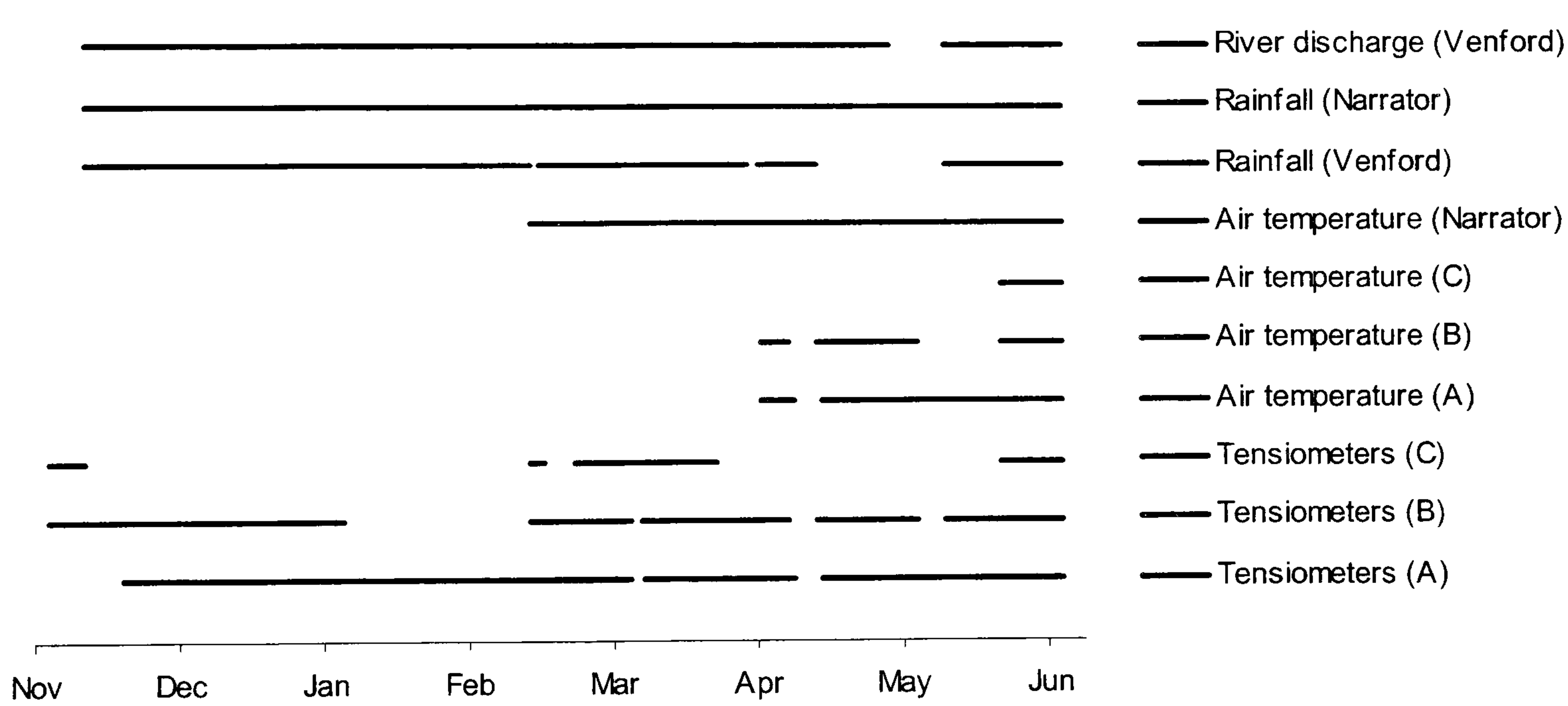


Figure 6.11: Recording periods of the tensiometers, runoff, and rainfall at different locations for 1999-2000.

One of the problems was the temperature effect on the pressure transducers. As the transducers used in this study were not temperature-compensated, temperature calibrations were carried out as described in Section 4.5.2. However, temperature also has a real effect on the soil tension. Water expands and contracts due to temperature, and so does the soil in the same order of magnitude. This will result in a daily fluctuation of the hydraulic head in the soil (Dowd and Williams, 1989; Hoelscher *et al.*, 1993;

Buchter *et al.*, 1999). Because the daily temperature fluctuation affects both the apparent and real tension, this effect could not be separated from soil tension variation due to soil water changes. However, when the tensiometer curves were compared to temperature and rainfall, most variation could be analysed and explained.

Temperature values were partly obtained directly from the logger and partly derived from temperature measurements from a recording station at Narrator, at the western side of Dartmoor (Section 4.2.5). Overlapping periods between both data sets showed a reasonable (r_s = 0.45, p = 0.000, data set of 1999) correlation on the 15 minute measuring interval time scale. Values for r_s are increasing with increasing time scale (r_s = 0.67 for a daily time scale). Therefore the Narrator data could be used with caution to fill data gaps in the Venford data set.

Figure 6.11 shows the recording periods for the different tensiometer nests, gauging stations and temperature. Recordings for the period at the end of February and beginning of March 2000 mostly overlap and therefore this period will be used mainly to explain the responses and to relate findings to other locations. Additional periods are added for clarity to explain rainfall responses at individual locations.

As the results are most clear for the midslope tensiometer site (B), the first section will explain the response at this location, followed by the results near the bottom and the top of the slope, respectively. The implications of the findings for hydrological pathways on different scale levels will be discussed in Section 6.8.

6.6.2 Midslope

The tensiometers on the steepest part of the slope (B) had the most complete data set of the three locations. The equipment was positioned 150 meters from the stream on a straight hillslope of 18°. Tensiometers were installed at 10, 20, 30, 40, 60, 80 and 100 cm depth.

A soil profile description was carried out for the upper 70 cm of the soil. The top 20 cm consisted of around 26% of organic matter, which could therefore be classified as an organic very dark brown O-horizon (Soil Survey, 1976). A black Bh-horizon with a sandy loam texture extends from 20 to 45 cm depth, followed by a very dark grey, gravely, loamy sand BC-horizon down to at least 65 cm depth with some large stones present.

Figure 6.12 shows a sequence of rain events between the 15th and the 20th February 2000. As is clear from this figure, the response at the 10, 20 and 30 cm tensiometers was strikingly similar to the rainfall-runoff response in the stream. An increase in head of 23.6, 14.7 and 11.8 cm, respectively could be observed at 19.00 hrs on the 15th February, when the tensiometer at 10 cm depth reached near-saturation. The pressure head at 40 cm, however, did not show any change. Although there were some fluctuations at 40 cm, these were not due to precipitation input, as the response was initiated before the start of the rain event.

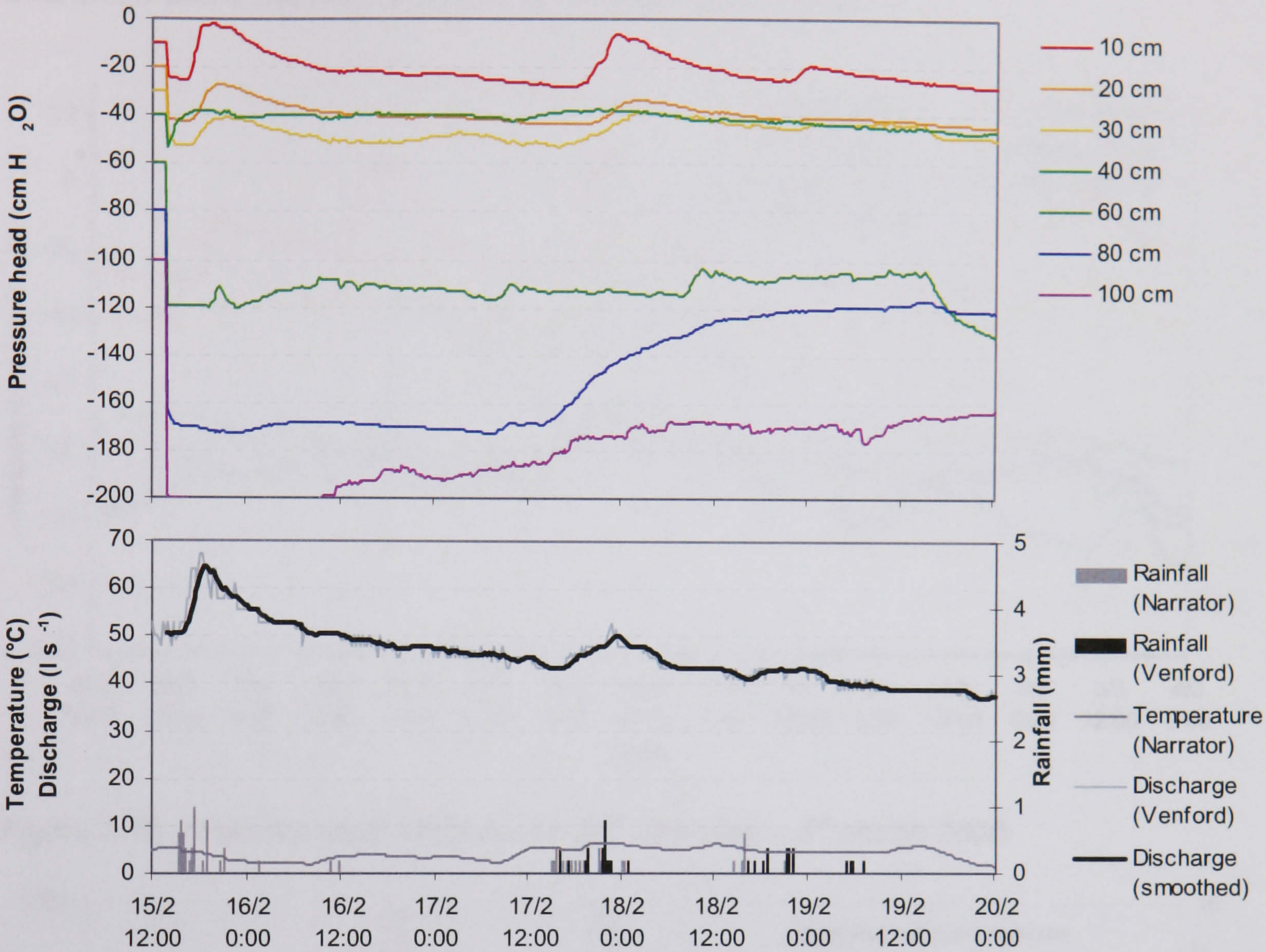


Figure 6.12: Pressure head, runoff and temperature and rainfall through time: 15th to 20th of February 2000 of the tensiometers at the steepest slope (site B).

This lack of response at 40 cm depth was also shown on other dates within the data set. The tensiometer at 60 cm did show a small response to the 5.4 mm rain event, with an increase in head of around 8 cm. During other rain events, no responses were observed with this tensiometer. At greater depths (80 and 100 cm), no head variations were recorded. The rise in head at 80 and 100 cm on the 15th February is attributed to the starting up phase of the installation of new pressure transducers, indicating that the tensiometers had not yet reached equilibrium.

Figs. 6.13 and 6.14 show a sequence of different intensity rain events, with 3.6, 45.6 and 44.4 mm of total rainfall, respectively. The string of events after 2nd March 12:00 totalled 18 mm of rainfall. Pressure heads in the top 30 cm again showed a straightforward rainfall response during both large and smaller rain events. The main difference between the different events was the saturation. The tensiometer at 10 cm depth reached saturation in both large rain storms and therefore show a certain amount of levelling out at a value of +10 cm H_2O, indicating that pressure heads could not be increased any further. Some standing water at the soil surface could have been possible at this moment, although the local slope would not allow a deep layer of water at this location.

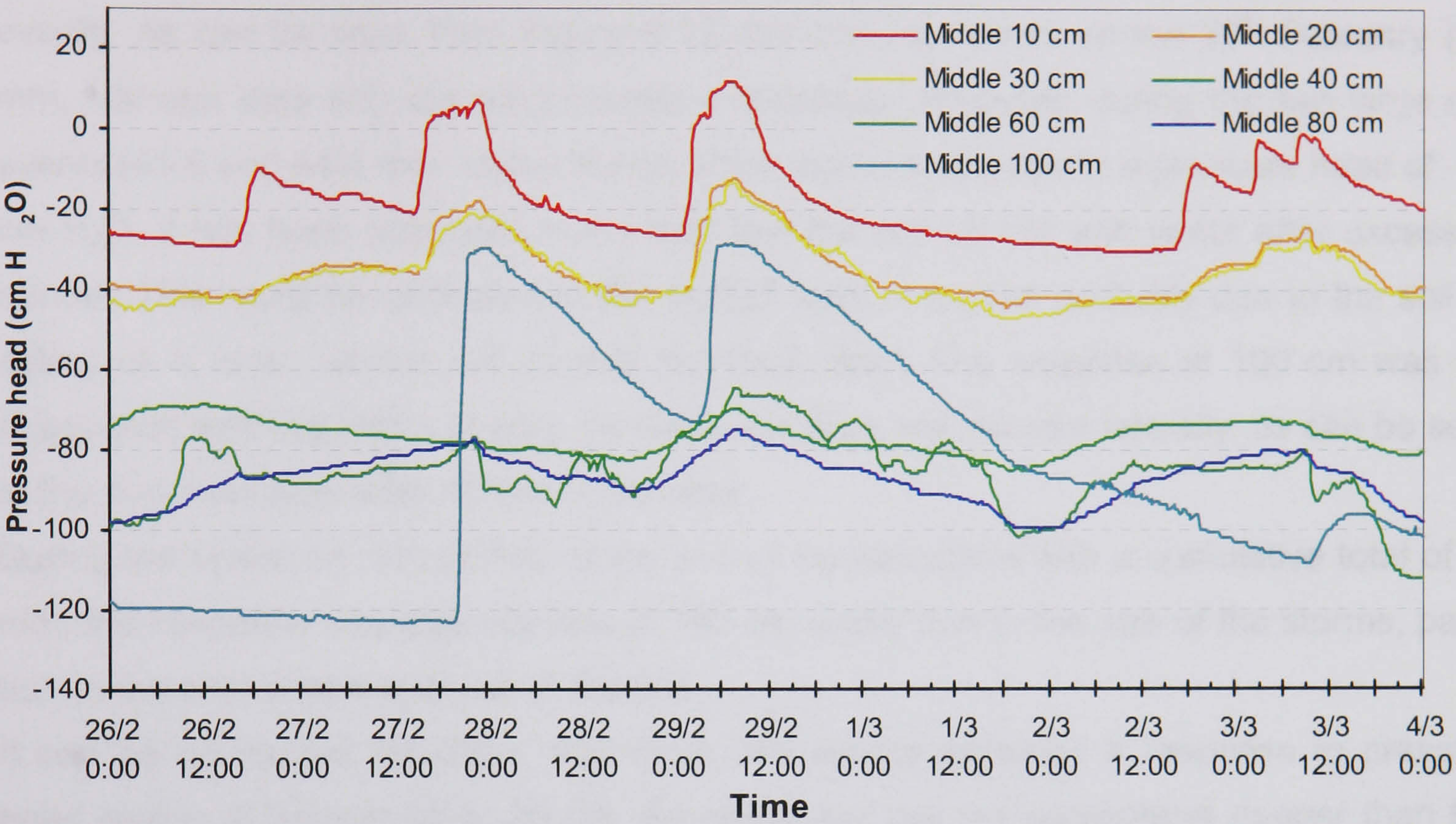


Figure 6.13: Pressure head midslope for 26th February – 4th March 2000.

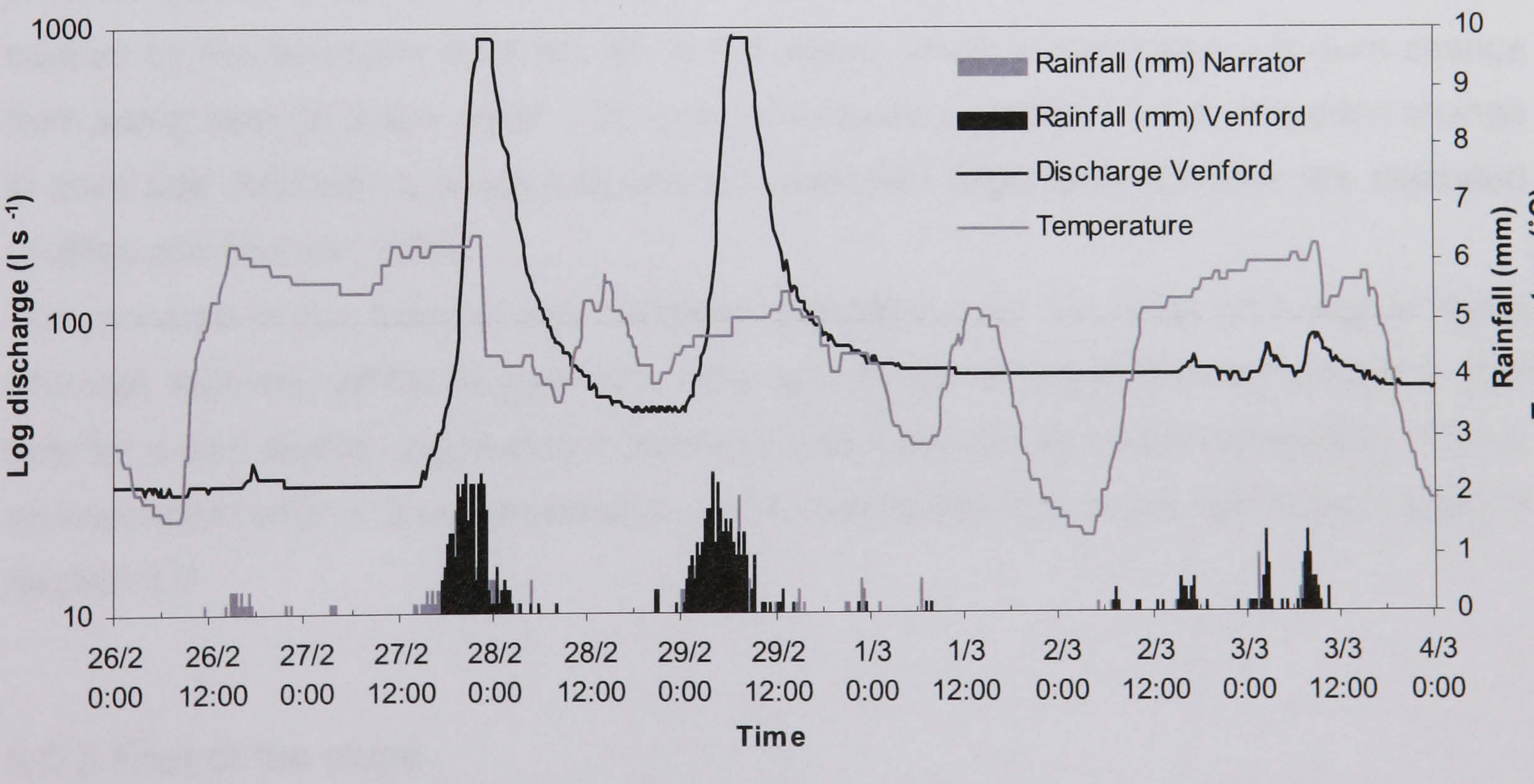


Figure 6.14: Rainfall-runoff and temperature for 26th February – 4th March 2000.

The pressure head at 40 cm again did not show a consistent response to rainfall in the data set, so this tensiometer was regarded as faulty and left out of the analysis. The tensiometer response at 60 cm was very sensitive to temperature fluctuations. However, its response showed a similar trend through time to these recorded near the soil surface, but more damped and with a longer recession after the rain event. The same applied to the tensiometer at 80 cm depth, with pressure head changes superimposed on temperature fluctuations.

Near the bottom of the soil pit, at 100 cm, the pressure head only responded to major rain events. As can be seen from Figure 6.13, the first rain event on the 26th February (3.6 mm, Narrator data set) did not generate a response. However, during the two large rain events (45.6 and 44.4 mm, respectively), there was a sharp rise to a pressure head of –30 cm H_2O. It has been observed in the field that the soil pit fills with water after excessive rainfall. This could be attributed to the rainfall itself, but most probably due to the soil pit acting as a 'sink', as the soil pit was not back filled. The response at 100 cm was not associated with this effect directly, as the water does not infiltrate laterally, as can be seen in the non-saturated state of the tensiometer.

During the scattered rain storms at the end of the sequence with a cumulative total of 18 mm, this response was also obvious at 100 cm, partly due to the size of the storms, partly due to the antecedent wetness of the soil.

It can be concluded therefore, that most rain events generate a response in pressure head mainly in the top 30 to 60 cm. As responses are not widespread deeper than this level, water must move laterally in the topsoil. Only during large rain events does water infiltrate quickly deep into the soil. The reason for this lateral water movement could be caused by the boundary from the Ah to B horizon, which incorporates a texture change from sandy loam to loamy sand. This forms a hydraulic constraint due to a sudden change in pore size distribution, which can only be overcome when both horizons are saturated (Kutílek and Nielsen, 1994).

The pressure heads suggest that complete saturation does not occur on a regular basis although soils are wet for long periods. When the topsoil does get to (near) saturation, it is only for a brief period, suggesting a relatively high saturated hydraulic conductivity. This is an important factor in the determination of soil water pathways, which will be addressed in Section 6.7.

6.6.3 Foot of the slope

The tensiometers at the foot of the slope were installed at around 45 meters from the stream on a slightly concave to straight slope of about 3°, situated within the variable source area (Section 5.4.3). The soil profile could be classified as a humus ironpan stagnopodzol (Section 6.3.1). A thin layer of amorphous black peat was overlying a black loamy sand Ah-horizon, extending to a depth of 30 cm. At this depth, a thin ironpan was present of about 1 cm in thickness. This ironpan overlaid a very dark brown B-horizon with a loamy sand texture. Because of the excessive wetness of the profile throughout the year, tensiometers were only installed above the ironpan (Section 4.5.1).

Due to technical problems, only a limited period of soil pressure head values could be obtained at the location near the stream. However, responses to rainfall seemed very consistent with the findings midslope in the upper soil horizons and were also very comparable to the rainfall runoff response in the stream.

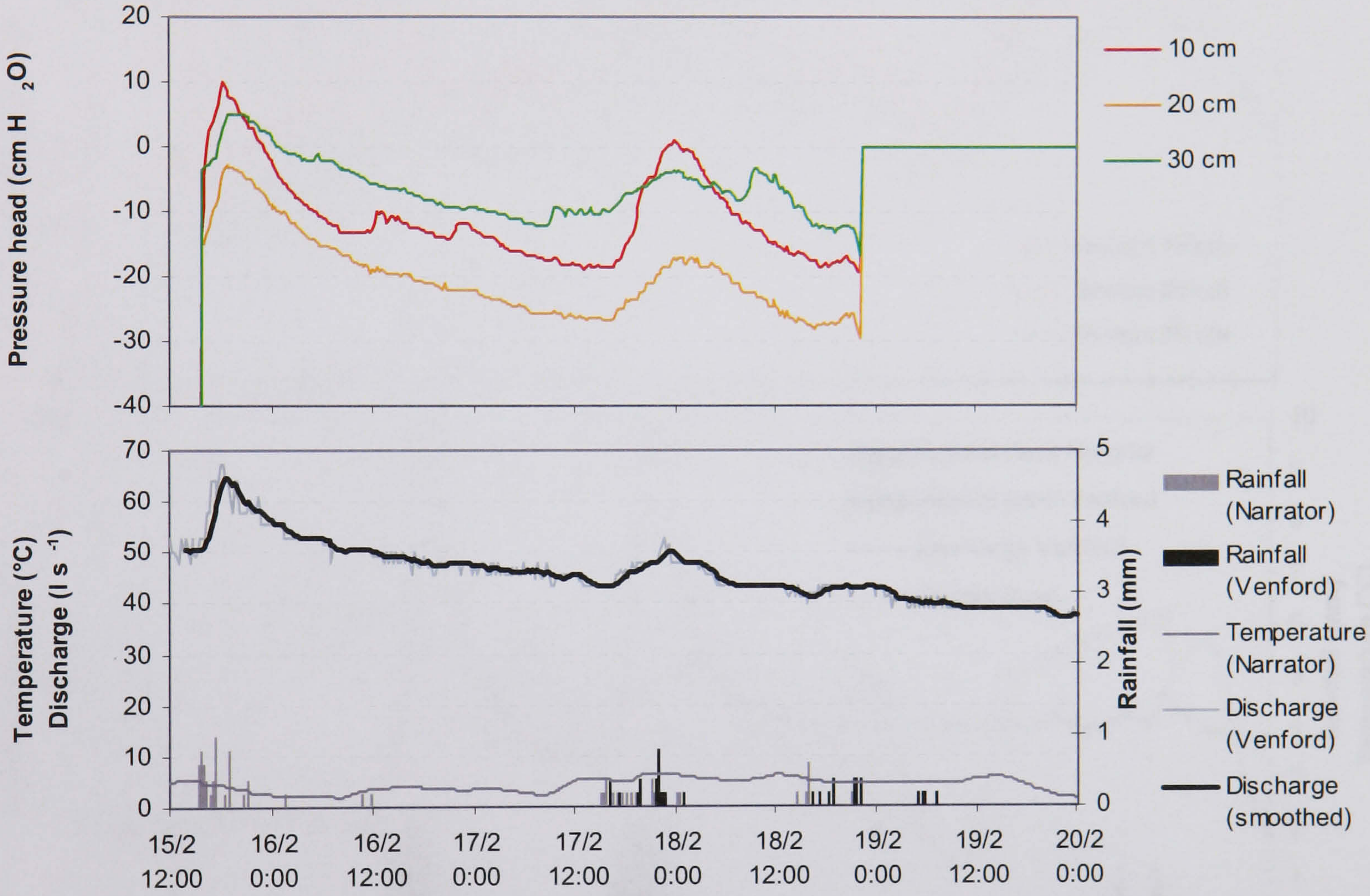


Figure 6.15: Pressure head, runoff and temperature and rainfall through time: 15th to 20th February 2000 of the tensiometers at the foot of the slope (site C).

Figure 6.15 shows the rainfall-pressure response for the same two consequent rain events in February 2000 as Fig. 6.12. The response to rainfall was very distinct. All three tensiometers, installed at 10, 20 and 30 cm below the soil surface, showed the same response time. The tensiometer closest to the soil surface showed the largest pressure change, 24 cm, decreasing with depth with 12 and 8 cm, respectively, during a rain event of around 5.4 mm (Narrator data set). The order of magnitude for all tensiometers was the same as the top tensiometers midslope (Section 6.7.2). The positive pressure head showed that the top soil became saturated during the peak at 10 and 30 cm depth.

Figure 6.16 shows a more complex pressure head response to rainfall during the same six-day wet period at the end of February 2000. Pressure heads showed a high correlation with temperature, and did not show an apparent response to rainfall. The positive pressure heads indicate saturated conditions at this location within the variable source area. Therefore, changes in pressure were minimal and the variation that was observed was mainly due to temperature effects on both the pressure transducers, as well as the tensiometers.

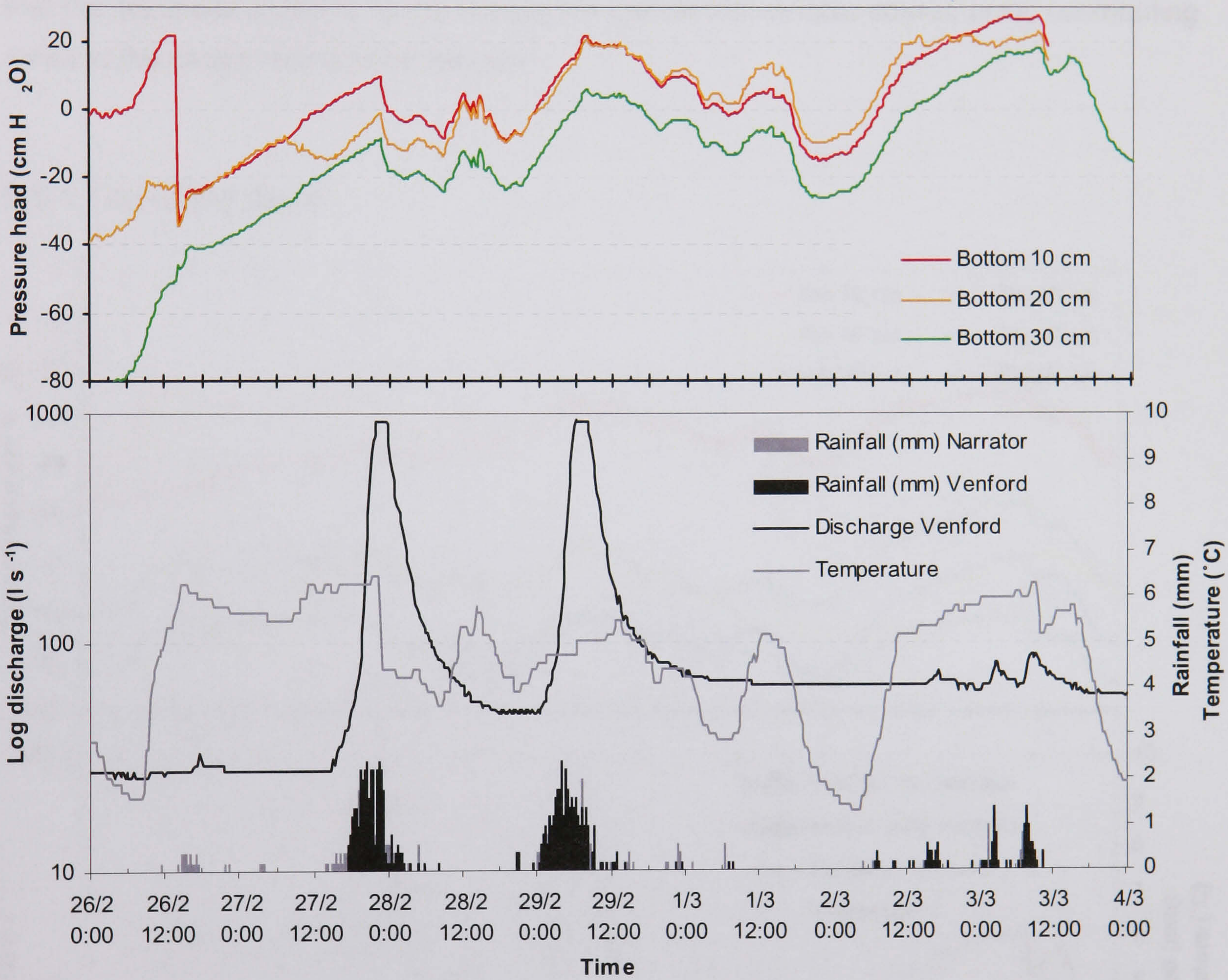


Figure 6.16: Pressure head at the bottom of the slope for 26th February – 4th March 2000 as a response of rainfall. Due to missing data from the study area rain gauge, rainfall from the Narrator dataset was used as an indication.

The response at 10 cm showed two clear peak times after the first rain event (Fig. 6.16). However, this was not found at greater depths. River discharge also hardly showed this response. One reason for the lack of response could be, that these were two very low intensity rain events. No rainfall data were available from the study area rain gauge. Rainfall data from the nearby Narrator catchment were therefore used instead. These data showed a small rain event of 0.4 mm for the first peak and it was assumed therefore that this was could also have been the case for the second peak. Obviously, timing and amount could deviate from the actual rainfall that occurred at the study site. The rainfall-pressure response at this location shows, that in the topsoil above an ironpan, pressure head values respond very similar to the stream, suggesting that rainfall is stored only briefly in the topsoil, but consequently rapidly being transported to the stream. This observation is consistent with the findings in the previous chapter, in which it was shown that the flat areas adjacent to the stream are part of the variable source area, contributing water to the stream throughout the year.

6.6.4 Top of the slope

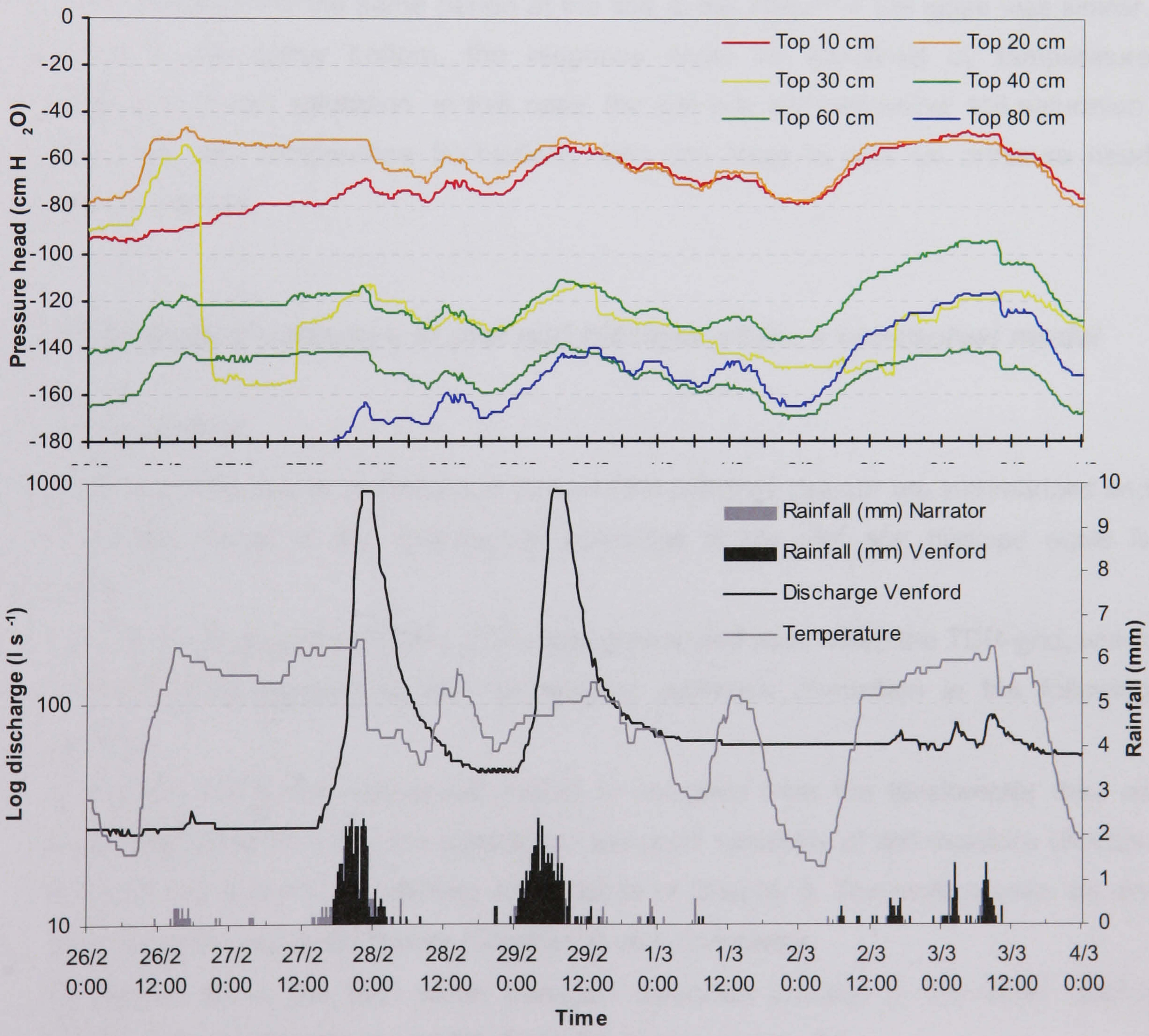


Figure 6.17: Pressure head at the top of the slope for 27th Feb – 4th March 2000.

The tensiometers installed at the top of the slope were situated 305 m from the river, with a local gradient of 6° on a convex hillslope. The soil was also classified as a humus ironpan stagnopodzol, with a very dark brown 5 cm thick Of-horizon overlying a black Oh-horizon 8 cm in thickness. From 13 to 39 cm depth a stony black B-horizon was situated with a loamy sand texture. A thin ironpan was formed at 40 cm depth, overlying another B horizon to at least 45 cm with a loamy sand texture. The profile was not described any deeper.

Data recorded at this location barely showed a response to rainfall. The pressure transducers used at this location were highly temperature sensitive, causing major fluctuations with only minor responses to rainfall. However, as the tensiometers responded in similar fashion, it was not expected that the equipment used was faulty.

Figure 6.17 shows the response of the period 26th February to the 4th March 2000. The response compared to the same period at the site at the bottom of the slope was similar. However, in the valley bottom, the response could be explained by temperature fluctuations at (near) saturation. In this case, the soil was still well below soil saturation. Unfortunately, the temperature fluctuations were too large to pick up pressure head changes in the soil.

6.7 Hydrological pathways at plot and hillslope scale: a conceptual model

6.7.1 Introduction

In this section, the results presented in this and the previous chapter are summarised and a conceptual model of the hydrological pathways at the plot and hillslope scale is proposed.

- Section 6.7.2 gives a summary of the topography and soils within the TDR-grid, which provides a background to the hydrological pathways discussion in the following sections.
- In Section 6.7.3, the conceptual model is compiled from the tensiometer data as presented in Section 6.6, the spatial and temporal variability of soil moisture (Section 6.4 and 6.5) and the contributing area results of Chapter 5. The section uses the dry and wet preferred states theory (Chapter 2) as a framework.
- In Section 6.7.4, the high water transport velocities involved in the water routing (Chapter 5) are discussed and fitted into the conceptual model.
- A summary of the proposed hillslope water pathways compiled from the results from Chapter 5 and 6 is described in Section 6.7.5.

6.7.2 Topography and soil properties within the TDR grid: a summary

The topography and soils within the TDR grid can be regarded as constant in the context of this study. So, gradient, altitude and soil properties as described in Section 7.3 could be regarded as the context to the development of a model of hillslope water pathways and are therefore summarised here.

The slope profile of the hillslope is mainly convex from the top to halfway down to the stream. A short, steep section divides the convex plateau from the concave to flat area in the valley bottom. Soils on the hillslope were typified by high groundwater levels or lateral seepage (Hogan, 1988) and are all formed in near saturated conditions close to the soil surface. Bulk density and porosity values were typical for peat soils. Total porosity and especially the volume of transmission pores is high, as shown by the water release curve. Most of the topsoils could be classified as peat (Soil Survey, 1976), and the organic matter content shows a significant positive correlation with gradient, and therefore with lateral drainage. Vertical saturated hydraulic conductivity values are relatively high in the area, but also show a high degree of variability.

6.7.3 Soil water and hydrological processes in different wetness states

'Dry' preferred state

Grayson *et al.* (1997) defined the 'dry' preferred state as a condition in which soil water movement is mainly determined locally by vertical fluxes. Evapotranspiration, infiltration, micro topography and soil properties are the main driving factors. Little water is moved laterally, only feeding into drier soil patches locally (Chapter 2). This definition also applies to the study area. In the catchment, in the dry preferred state, soil moisture patterns are largely heterogeneous. In geostatistical terms, the correlation length of the semivariograms is short. Semivariograms could be modelled only over a short active distance, so the correlation between locations decreases rapidly with distance. As a result kriged soil moisture patterns revealed a high degree of 'patchiness' (Section 6.4). At the driest occasion, the sampling distance was too short to properly fit a model to the semivariogram. An experiment carried out on the entire hillslope, showed that this heterogeneous pattern was representative for the area (Section 6.4.4) in the dry state.

Tensiometer recordings within the TDR grid showed a quick response to rainfall in the topsoil mainly (Section 6.6). Following the results presented by Grayson *et al.* (1997), rainfall on the hillslope in the study area is mainly stored in the topsoil in this dry preferred state during small and medium-sized rain events. The soil moisture – stream discharge relationship shows the importance of the large volume of storage available, as with increasing soil moisture, discharge levels show a relatively small increase.

Therefore, it is suggested that the hillslope does not contribute to storm runoff during the dry preferred state. This explains the minimum contributing area values below 10% of the total area of the watershed (Section 5.4.3). So, precipitation in the dry preferred state is transported to the stream by saturation overland flow and shallow subsurface runoff from the variable source area only. The overland flow has been observed in the field and the recorded pressure heads in the valley floor (Section 6.6) showed the shallow subsurface response. The rapid rise and fall in the rainfall-runoff response was in the same order of magnitude and time scale as the tensiometer response in the valley floor (Section 6.6). After the rainstorm, the discharge and pressure heads rapidly decrease as the overland flow and subsurface flow cease. This similarity showed that velocities normally associated with overland flow (Section 5.4.4) could partly explain the rapid response.

Wetness threshold

When the average soil moisture content increases on the hillslope, a wetness threshold is reached, dividing the dry from the wet preferred state. This wetness threshold could be defined by an average soil moisture content of the TDR-grid of around 0.60 cm^3 cm^{-3} (Section 6.4.3). However, the value of this soil moisture threshold may change outside the TDR grid, and there was a need to define the threshold with additional parameters. The wetness threshold was therefore also characterised by variables independent on measured soil moisture values (Section 6.4.3). The definition in geostatistical terms was determined by the active distance of the semivariogram (between 100 – 200 m) and the correlation length (25 to 150 m). Antecedent wetness conditions, defined by the API_{18} should be between 50 and 70 mm. Below these criteria, the hillslope is in the dry preferred state, and if values are higher, the wet preferred state is reached. These criteria could also be applied to the grazing grid within the study area, but should be used with caution at different locations outside the study catchment.

'Wet' preferred state

During the wet preferred state, above the wetness threshold, soil moisture patterns on the hillslope change from a very heterogeneous appearance to a homogeneous wetness. As stated earlier, this behaviour of soil moisture patterns has been observed in a humid climate by Western *et al.* (1999). Additionally, similar observations in semi-arid conditions in Spain are reported by Fitzjohn *et al.* (1998).

In the study area, soil moisture patterns are characterised geostatistically by long correlation lengths and a much longer active distance than in the dry preferred state. As a consequence, kriged soil moisture plots show large, connected areas with similar soil moisture contents. Grayson *et al.* (1997) showed that in this state, soil moisture distributions have a high degree of organisation, mainly influenced by the topography. This preferred state could therefore be described as determined by non-local controls (Grayson *et al.*, 1997). Gradient increasingly influences water movement in the topsoil.

At the plot scale, both midslope and in the valley bottom, pressure heads show a rapid response in the top 30 cm to rainfall (Section 6.7). The rapid response is comparable to the rainfall-runoff response in the stream in terms of timing and magnitude, similar to that in the dry state. The fact that tensiometers do not show a response deeper in the profile suggests that water flows laterally in the near surface horizons (Section 6.6). Wheater *et al.* (1993) reported a similar response in the Allt a' Mharcaidh catchment in north-east Scotland. They showed that the tension in the topsoil changed more rapidly than the subsoil as a response to the rainfall, indicating a large lateral component of the flow.

In the study area, areas of different soil wetness therefore can become hydraulically connected, and water is redistributed, forming a more homogenous pattern. The shape of the water release curve (Section 6.3) could explain the process that determines the change from local to non-local control. The curve suggests that above the wetness threshold, the transmission pores start filling up and therefore the lateral hydraulic conductivity increases rapidly (Van Genuchten, 1980; Deeks, 2000, pers. comm.; Section 6.5), forming hydraulic connections between areas with high moisture levels. As a result, water can be transported down the hillslope over larger distances than in the dry state, and would eventually reach the stream.

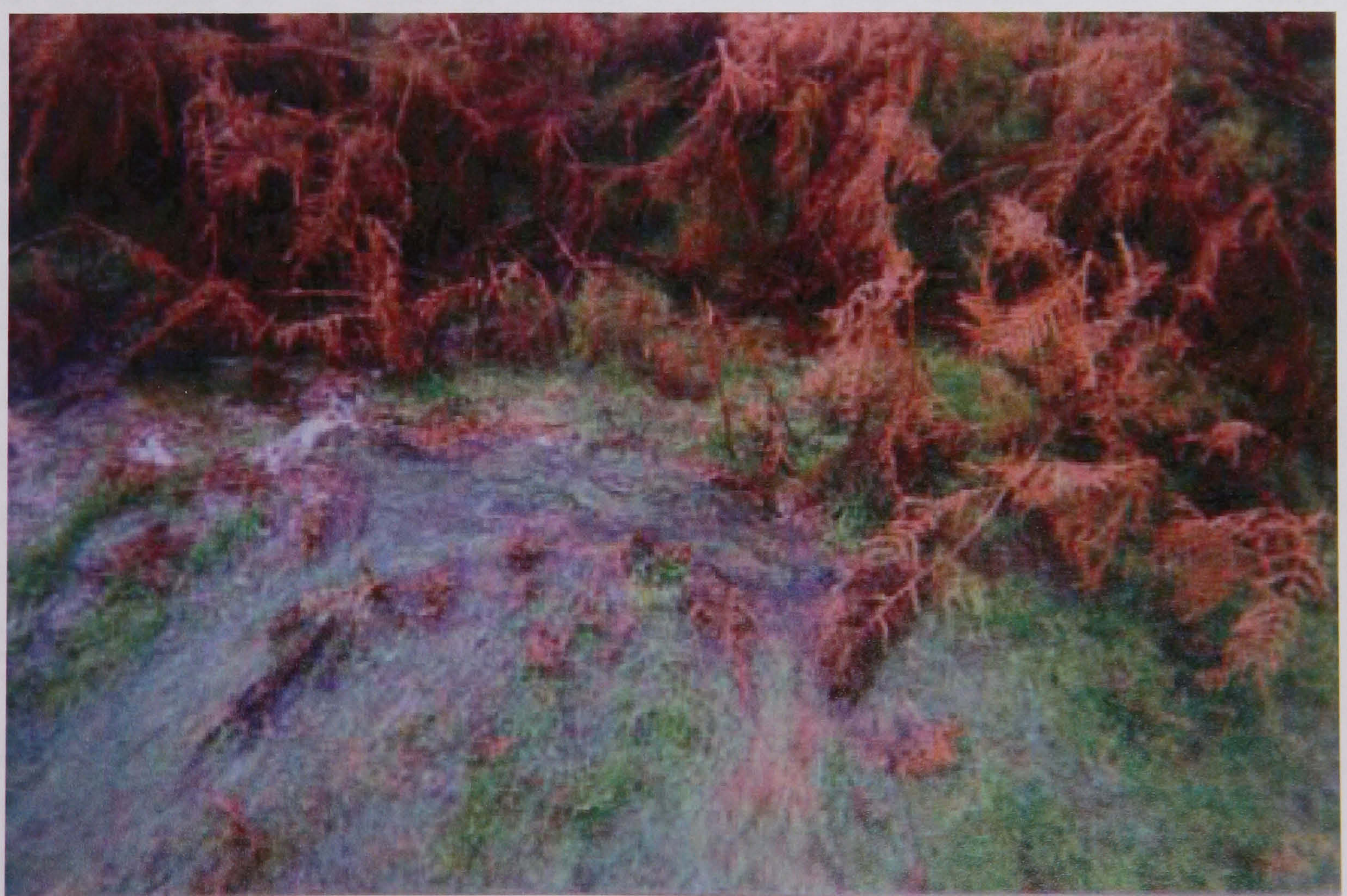


Plate 6.1: Springs have been observed locally in wet conditions.

This process could account for the higher discharge levels in the wet segment of the soil moisture-runoff curve (Section 6.6), in which discharge increases rapidly with increasing soil moisture content. The process could also explain the relatively high runoff in wet conditions (Section 5.3.3), with a minimum contributing area of up to 65% of the catchment area.

Overland flow in the valley bottom of the watershed is evident, and on some selected sites in the catchment springs have been observed in extremely wet conditions (Plate 6.1). Overland flow in the catchment was mapped during wet conditions and subsequently digitised in a GIS. However, the extent of these areas could not account for the volume of water in the stream associated with the rain event. Therefore, water pathways have to be expected in the subsurface as well, as also has been shown by the tensiometer responses (Section 6.6). If most of the water transport on the hillslope occurs as subsurface flow, the transport must involve high velocities, as shown in Section 5.4.4. These velocities will be discussed separately in the following section.

6.7.4 Water transport velocities

It was observed that the time to peak of the hydrograph increases with increasing rainfall. However, rain events exceeding 20 mm, or, in other terms, storms in which more than the variable source area (defined by an extent smaller or equal to 10% of the catchment area) is contributing do not show an increase in time to peak (Section 5.4.3). For these conditions, velocities from 9 to 90 m hr^{-1} have been calculated (Section 5.4.4). These velocities are in the same order as overland flow, which has been found to range between 36 and 1800 m hr^{-1}, depending on slope and surface roughness (Dunne, 1978) and between 108 and 540 m hr^{-1} on a slope of 21°, depending on surface roughness and vegetation (Emmett, 1978).

The calculated velocities required for the rapid rainfall-runoff response are more than two orders of magnitude higher than the saturated hydraulic conductivities observed in the study area (typically 0.4 m hr^{-1}), making throughflow (interflow) highly unlikely as the main process. Moreover, it has also been observed, that during these wet conditions soils are not always fully saturated, so that the *actual* hydraulic conductivities are much lower (Van Genuchten, 1980).

The high velocities associated with large rainstorms prohibit throughflow (Whipkey and Kirkby, 1978). The lack of surface water excludes (Hortonian) infiltration and saturation excess overland flow pathways (Dunne, 1978; Dunne, 1983). Therefore, only macropore flow, pipeflow (Gilman and Newson, 1980; McDonnell, 1990) or pressure waves (Rasmussen *et al.*, 2000; Williams, *et al.*, 2002) could explain the process.

It has been shown from the tensiometer data that most of the water on the hillslope is transported through the topsoil (Williams *et al.*, 2002 and Section 6.7). Therefore, macropore flow in the topsoil could be an explanation for the fast response if the soil conditions were saturated (Beven and Germann, 1982). This flow can only occur when there are sufficient large continuous pores. The soil water release curves have shown, that there is a high percentage of large (transmission) pores, which is valid for all curves established. Especially the larger transmission pores are high in abundance, as the break in slope of the curve near tensions of -30 cm indicates.

Additionally, locally observed springs could provide some evidence of pipeflow during wet conditions, but the extent could not account for the rapid rainfall-runoff response entirely.

Williams *et al.* (2002) introduced a new interpretation of hillslope storm flow generation within the watershed. Pressure waves, as studied by Rasmussen *et al.* (2000) could be a possible explanation of the rapid response. Although in their study, the velocities are still slower than observed in the catchment, it is evident that pressure wave velocities are many times higher than matrix flow. This means, that the velocities of up to 90 m hr^{-1} found in the study area can easily be met, even if the saturated hydraulic conductivity averages at 0.4 m hr^{-1}. Also, in the experiment of Rasmussen *et al.* (2000), porosity values were much lower (0.53 cm^3 cm^{-3}) than observed in the study catchment (0.7 to 0.9 cm^3 cm^{-3} on average, depending on depth), and the soils in the watershed are generally wetter, increasing the volume of the pressure wave to move through. This decline in porosity with depth, in combination with the observation by Rasmussen *et al.* (2000) that the pressure wave decreases with depth, indicate that pressure waves could travel laterally down the slope.

These findings are similar to the findings by Tani (1997) on a steep forested hillslope. He noted the importance of macropores or transmission pores in this process, which was shown in the study area to be of main importance. Large pores, taken up by macropores, cracks and pipes, may enhance this process, and is supported by the water release curve. When soil conditions are becoming wetter, the ability of the soil for the transmission of the pressure wave is enhanced (Williams *et al.*, 2002). Therefore, the mechanism presented here does not exclude a combination of pressure waves with macropore or pipeflow. Pressure waves could be pushing water into macropores, cracks or pipes, which consequently is transported down the slope. This, for example, could explain why McDonnell (1990) observed 'old' water flowing from macropores into pits.

It could therefore be proposed, that a combination of pressure waves, macropore flow and pipeflow could account for the rapid rainfall-runoff response during the wet preferred state within the study catchment. Preliminary results from isotopic analyses conducted in

January 2002 have suggested that rainwater and storm runoff are distinctively different (Leng, 2002, pers. comm.).

6.7.5 Hillslope water pathways: conclusion

In combination with the results presented in this and the previous chapter, storm response can be characterised for small and large rain events (Williams *et al.*, 2002).

During a small storm (smaller than 20 mm, as defined in Section 5.3), initially the discharge is determined by baseflow. The variable source area feeds water into the stream, mainly by shallow subsurface flow from the variable source area. In addition, as the storm progresses, saturation excess overland flow from the variable source area also contributes to the flow. Although travel times are long, the distance to the stream is short, so these soil water transport processes could explain all peak volumes during small storms (Williams *et al.*, 2002).

During larger storms, as the storm begins, the process is the same as for small rain events. The tension in the topsoil changes more rapidly than the subsoil as a response to the rainfall, indicating a large lateral component of the flow. Dry and wet areas on the hillslope are becoming homogeneously wet, and become connected to the variable source area and consequently to the stream. As a consequence, discharge levels rise rapidly during this connection. Similar to the core experiment by Rasmussen *et al.* (2000), the rainfall in the catchment triggers a pressure wave response, causing a redistribution of water through the topsoil. This wave travels laterally down the slope, and near the bottom, water is being "pushed" into the saturated variable source area, supporting the storm runoff (Williams *et al.*, 2002). The presence of large pores enhances the possibility of the pressure wave to propagate (Williams *et al.*, 2002). The relatively high proportion of large pores in the study area suggest, that a combination of pressure waves, macropore flow and pipeflow could be the main soil water transporting process in the study area during wet conditions.

This conceptual model forms the basis for the understanding of the impact that management factors like burning and grazing could have on the transport of water within the catchment, both in time and magnitude. In the next chapter, Chapter 7, the (indirect) effects of land management on the vegetation cover and composition and on the topsoil are studied. The consequences upon water pathways, with a focus on the topsoil, are outlined in Chapter 8.

Chapter 7: Vegetation in relation to soil characteristics

7.1 Introduction

In this chapter the vegetation is described at the hillslope scale within the TDR grid using a field survey and at the catchment scale, using air photo classification. The presence of vegetation species is related to soil properties, topography and grazing. With reference to the results of this chapter, combined with findings from Chapter 6, the relationship between vegetation, soil and topography will be used to explain soil moisture patterns observed at the hillslope scale.

7.2 Vegetation distribution

This section describes the vegetation cover at the hillslope and catchment scale, with the aid of individual plant species (Section 7.2.1), TWINSPAN (7.2.2) and air photos (7.2.3), as an introduction to moisture-vegetation relationships discussed later in this chapter.

7.2.1 Vegetation composition within the TDR grid

Vegetation descriptions were carried out within the TDR grid (Section 4.4.1). In order to study the vegetation distribution, plant species coverage was compared to position on the hillslope expressed as distance from the stream following Kent and Coker (1992). A 20-period moving average *vs.* distance (to the stream) plot was created for all 151 vegetation quadrats (Fig. 7.1). Averages were taken of the percentage cover of all individual species, and the 20-period moving average was chosen to filter out the highly variable nature of the different species over the hillslope.

In general, it was found that heather species were more abundant at higher elevations on or near the plateau (Fig. 7.1). *Calluna vulgaris* especially showed this higher abundance, as this species was mainly found in two patches on the upper half above the steepest part of the slope. This was in accordance with findings by Kent and Wathern (1980) who showed that *C. vulgaris* heathland mainly occurred just above the steepest slope in the Narrator catchment on Dartmoor.

Erica cinerea was found halfway and near the top of the slope. *Erica tetralix* was scattered in low densities over the entire hillslope, but with a higher occurrence at the steepest part. Generally this species is associated with slightly wetter, boggy conditions in comparison to other heath species (Stace, 1997). However, soil moisture measurements indicated a tendency to slightly drier conditions and shallower peaty topsoils at this part of the slope.

Possibly other factors, like grazing pressures and/or other soil properties play a more important role here. Indeed Kent and Wathern (1980) argued that the occurrence of heathy species in the Narrator catchment were not only determined by soil moisture, but also by land management factors grazing and burning.

Festuca ovina showed a clear increasing trend from the bottom to the top of the slope, with a higher coverage in areas with a lower coverage of heath species, indicating its preference for drier conditions (Rose, 1989) and shallow, well-drained soils (Hubbard, 1984). It is known to be comparatively nutritious for sheep and occurs only in areas with at least some grazing (Weaver *et al.*, 1998). It can withstand high grazing pressures (Hubbard, 1984).

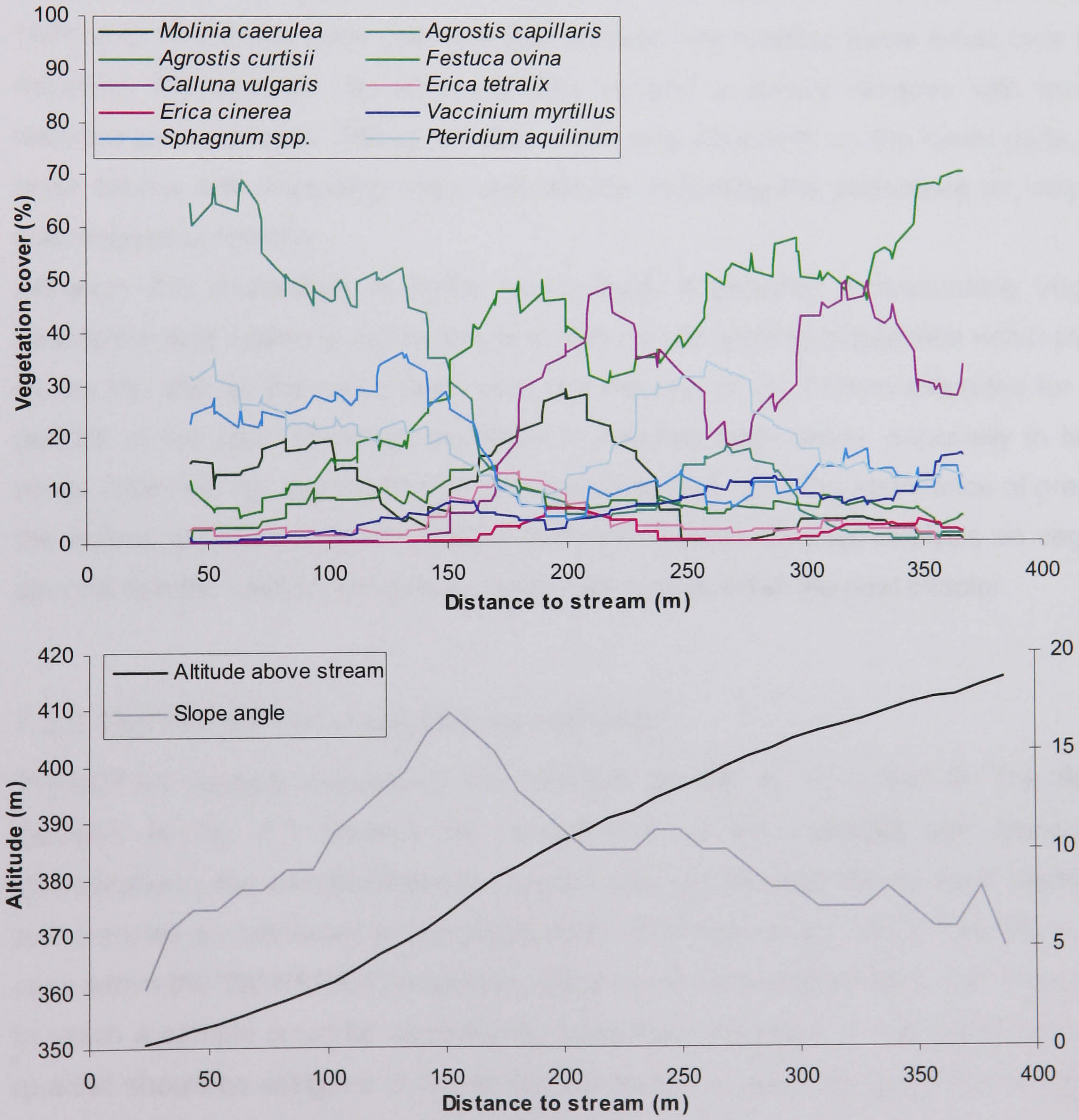


Figure 7.1: General distribution of vegetation along the catena. Lines indicate 20-period moving averages.

Agrostis capillaris showed an opposite trend, with a large coverage up to 150 metres from the stream, up to the steepest slope, and with a rapid decline afterwards. However, between 250 and 300 metres, a local higher coverage was found. *Agrostis curtisii* was fairly constant throughout the catena. The coverage of *Molinia caerulea*, preferring wet soils with a fluctuating water table (Rutter, 1955; Rose, 1989) was highest in the valley bottom, but also just above the shoulder at 200 metres from the stream. This species is known to exclude other flowering plants (Hubbard, 1984) and grasses (Weaver *et al.*, 1998), which could be important for the understanding of the absence of species otherwise expected in these wet areas.

The abundance of *Pteridium aquilinum* (bracken) was highest on the valley floor and near the plateau, between 250 and 300 metres. From the comparison of air photos from 1969, 1976 and 1992 it has been observed that bracken has invaded these areas over the last decades. The species *Vaccinium myrtillus* showed a steady increase with increasing distance to the stream. *Sphagnum* spp. were only abundant on the lower parts, with a rapid decline with increasing slope and altitude, indicating the preference for very wet to waterlogged conditions.

Although this description is rather generalised, it provides a reasonable vegetation description and relates to soil moisture conditions and grazing distribution within the area. At the top and on the valley floor, soils are wet and at the bottom saturated for certain periods of the year. *Pteridium aquilinum* is invading large areas, especially in less wet areas. Near the top, the heather cover is relatively high, and the abundance of grasses at the bottom indicates a higher grazing pressure. A more detailed analysis on vegetation species and the relation with grazing pressures is outlined in the next chapter.

7.2.2 The TWINSPAN vegetation classification

TWINSPAN analysis resulted in four different groups: A, B, C and D. The flowchart depicted in Fig. 7.2 explains the classification of the quadrats into groups. Most classifications, like soil classifications for example, can be regarded as 'hard' classification and samples are attributed to one single class (Franssen *et al.*, 1997). Yet, this is not the case within the TWINSPAN framework, which could be described as a 'soft' classification, in which a sample could be attributed to more than one class. In this case, a vegetation quadrat should be assigned to one of the two branches, and consequently be assigned to that group. This should be repeated until the group (A, B, C or D) has been established.

Group A can be regarded as the heathy species, with *Calluna* and *E. tetralix* present, and a high cover of *V. myrtillus*. *Molinia caerulea* is also present. This group represents the typical semi-natural vegetation community for moorlands such as Dartmoor with little grazing (Weaver *et al.*, 1998). The presence of *Molinia* and *E. tetralix* indicates the relation to blanket bog communities due to their moisture tolerance (Kent and Wathern, 1980). Although this group is a good reflection of semi-natural vegetation, other factors are also important. *Festuca ovina* has been associated with grazing (Kent and Wathern, 1980), and is known to decline when grazing is excluded completely (Weaver *et al.*, 1998).

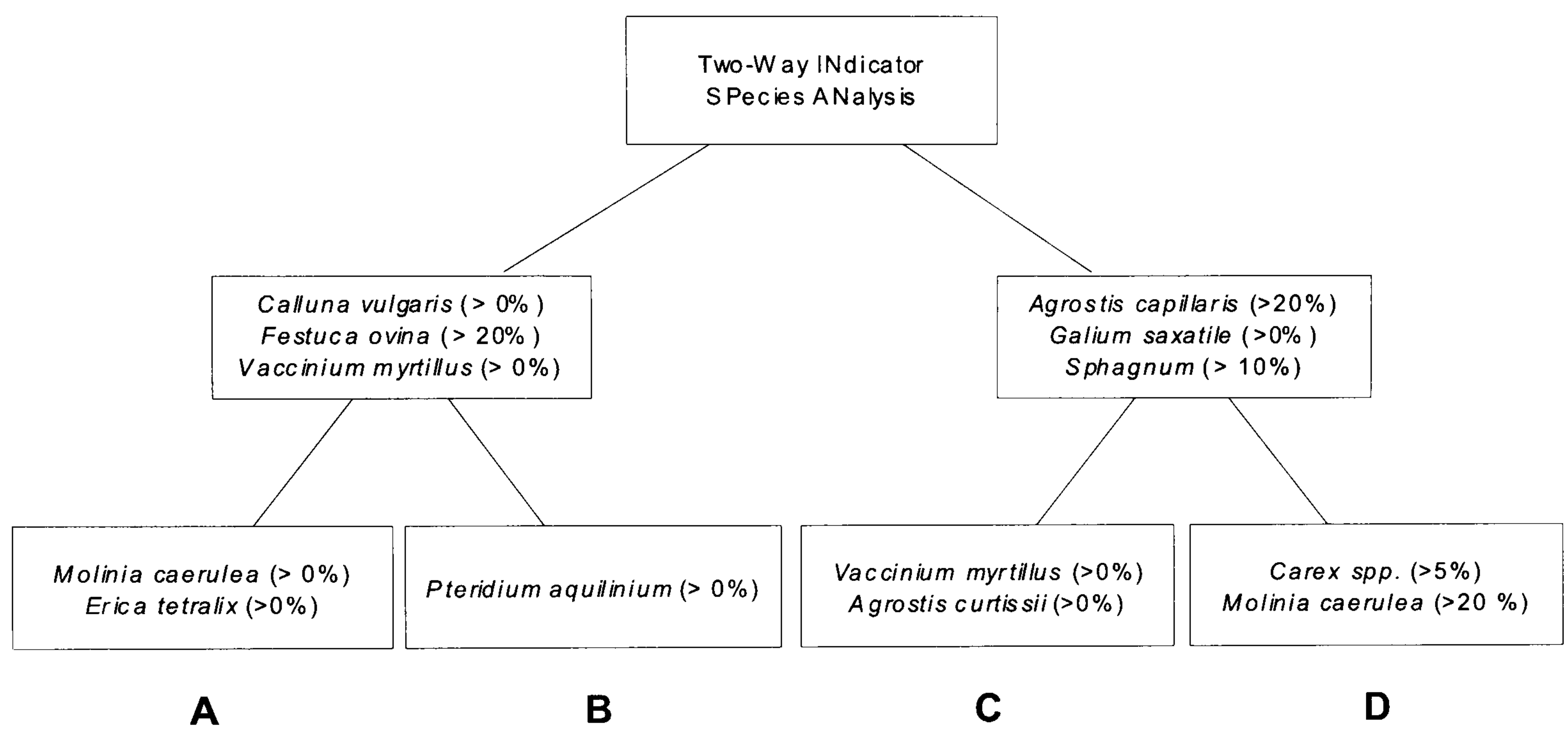


Figure 7.2: Results of the TWINSPAN classification.

Group B is similar, but with no *E. tetralix* or *Molinia* present, typical for heathland under light but present grazing. It also shows an increased cover of bracken (*Pteridium aquilinum*), which is invading large areas on Dartmoor (Kent and Wathern, 1980; Williams *et al.*, 1987). Bracken prefers slightly drier, better-drained soils (Kent and Wathern, 1980), and therefore this group also reflects less wet conditions than group A.

Groups C and **D** are more dominated by grass species and therefore were even more a reflection of grazed areas with a decline or even loss of heather (Sydes and Miller, 1988; Hill *et al.*, 1992). Both showed high cover of *Agrostis capillaris*, but also *G. saxatile* and *Sphagnum* mosses. *A. capillaris* has been shown to increase only when *Calluna* decreases, and so does *A. curtisii* (Weaver *et al.*, 1998), hence indicating higher grazing pressures. Group C also shows some cover of *V. myrtillus* and *Agrostis curtisii*, whereas group D has a large cover of *Molinia* and more than 5% cover of *Carex spp.*

It could be concluded, that the TWINSPAN classification not only shows a gradient in grazing pressures (with pressures in A lower than in B, which in turn was lower than the vegetation groups C and D), but also clearly indicates a moisture gradient. Groups A and D prefer the wettest areas, and groups B and C favour significantly drier sites. This was confirmed with a Kruskal-Wallis test on both the whole hillslope data set (n = 151) as well as the data set with soil properties only (n = 23), which is presented later in this chapter.

The geographical distribution over the hillslope showed (Fig. 7.3), that class B was abundant on the uppermost half of the grid in general, with class A forming the border between the two halves. On the lower part, a mosaic of the other three groups (A, C and D) was present.

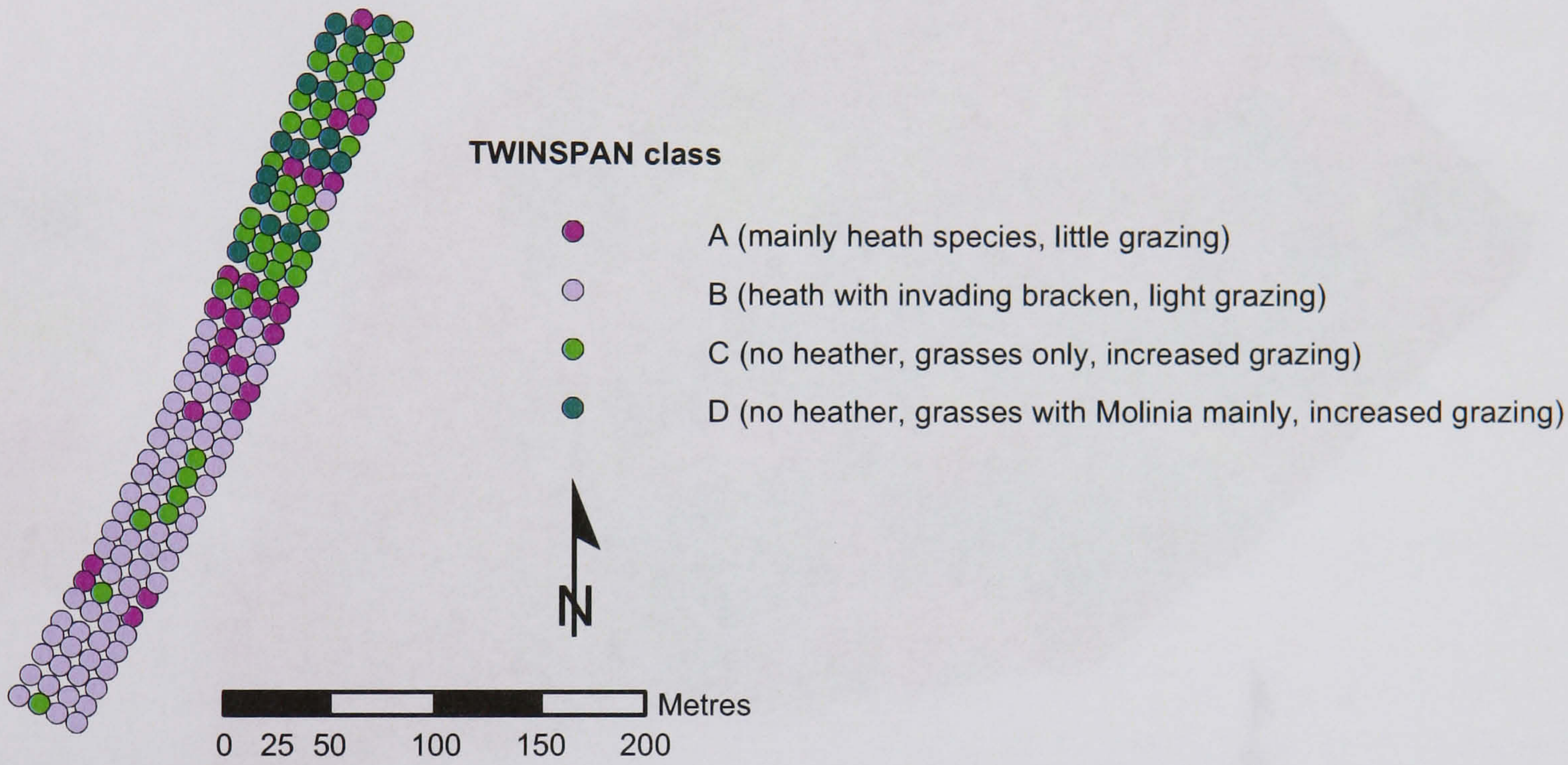


Figure 7.3: TWINSPAN vegetation classes across the TDR-grid.

7.2.3 Supervised air photo vegetation classification

Single vegetation species were classified into four different groups as described in the previous section. However, to be able to extrapolate results from the hillslope scale to the whole watershed, readily available or easy obtainable vegetation data was required. Vegetation cover estimates therefore need to be carried out throughout the catchment. This could involve a large amount of time in field surveys. Instead, air photos were used to create a supervised vegetation classification at the catchment scale. The methodology is outlined in Section 4.6.3.

On the basis of the air photo of 1992 (DNPA), four different vegetation types could be distinguished, based on the reflectance in the red, green and blue bands. The vegetation classes could be specified more precisely with field observations:

- **HG**: Heather-grass mosaic, with *Calluna* and *Festuca ovina* as main species;
- **GG**: Gorse (*Ulex spp.*) and/or long grasses, mainly *Molinia caerulea*;
- **BG**: Predominantly *Pteridium aquilinum* with an underlying layer of short, mainly grazed grasses (*F. ovina* and *A. capillaris*);
- **SG**: Grasses with a very short sward height (*F. ovina* and *A. capillaris* mainly).

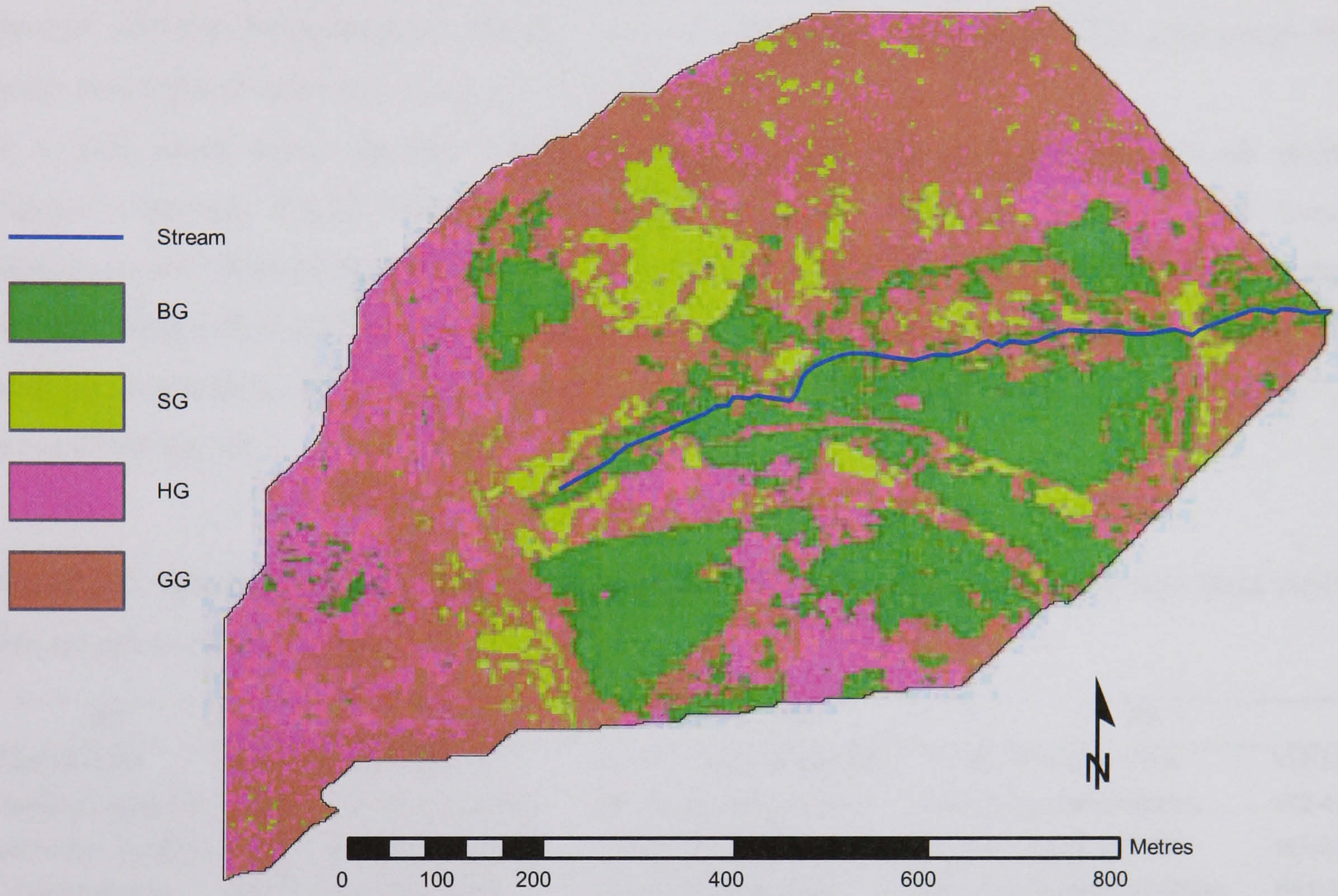


Figure 7.4: Vegetation classes based on the 1992 air photos.

Unfortunately, as detailed information on the occurrence of single species was not available, the groups could not be classified into generally accepted NVC-classes as described by Rodwell (1992).

The HG class showed close similarities with the TWINSPAN A group (Section 7.2.2). BG was similar to B. The correspondence between SG and GG and C and D was less clear, but in general the classification showed the same pattern as the TWINSPAN-analysis of the TDR-grid area. Therefore it was assumed that the air photo classes reflected the vegetation cover of the entire hillslope in an appropriate manner. Both classifications showed a high abundance of heather near the top of the slope, but also bracken in large areas (Fig. 7.3 and 7.4). Lower on the slopes, grass is occupying large areas, possibly due to higher but spatially varying grazing pressures. The main difference was the GG group, which showed a large *Ulex spp.* coverage in the northern part of the catchment

(Fig. 7.4), but this species was mainly absent in the southern part of the watershed. The spatial distribution of the different vegetation classes at the catchment scale will be described and discussed in detail in Chapter 8.

7.2.4 Vegetation in the catchment – comparison between scales

A comparison was made between the vegetation descriptions made using air photo groups and the frequency and abundance of vegetation within the TDR-grid since the scale and type of approach were so different.

In a GIS, plant cover sample locations were grouped into the four different air photo classes (Section 7.2.3). Within each group, the frequency and abundance of every species were determined. Frequency is defined as the number of times the species occurs, irrespective of the cover. The term abundance is used to describe the cover of the species, regardless of how frequent it is among the samples (Rodwell, 1992). Table 7.1 shows the results.

Table 7.1: Species frequency and abundance within the TDR plant coverage data using the air photo classification.

HG		GG		BG		SG	
Festuca ovina	V(1-5)	*Festuca ovina*	V(2-5)	*Pteridium aquilinum*	V(1-5)	*Sphagnum spp.*	V(1-5)
Pteridium aquilinum	IV(1-4)	*Vaccinium myrtillus*	IV(1-3)	*Agrostis capillaris*	IV(2-5)	*Agrostis capillaris*	V(2-4)
Vaccinium myrtillus	IV(1-3)	*Pteridium aquilinum*	IV(1-3)	*Sphagnum spp.*	IV(1-4)	*Galium saxatile*	V(1-2)
Calluna vulgaris	IV(1-5)	*Calluna vulgaris*	III(1-5)	*Festuca ovina*	IV(1-5)	*Pteridium aquilinum*	IV(1-3)
Sphagnum spp.	III(1-4)	*Sphagnum spp.*	III(1-5)	*Vaccinium myrtillus*	III(1-3)	*Festuca ovina*	IV(2-4)
Agrostis curtisii	III(2-3)	*Carex spp.*	III(1-5)	*Galium saxatile*	III(1-3)	*Vaccinium myrtillus*	IV(1-2)
Agrostis capillaris	II(1-5)	*Molinia caerulea*	II(1-5)	*Carex spp.*	II(1-5)	*Agrostis curtisii*	III(2-3)
Molinia caerulea	II(1-5)	*Agrostis capillaris*	II(2-5)	*Calluna vulgaris*	II(1-5)	*Polytrichum commune*	II(2-3)
Erica tetralix	II(1-3)	*Agrostis curtisii*	II(2-4)	*Agrostis curtisii*	II(1-3)	*Carex spp.*	II(1-2)
Carex spp.	II(1-3)	*Erica tetralix*	II(1-3)	*Molinia caerulea*	II(2-5)	*Molinia caerulea*	I(4)
Potentilla erecta	II(1-2)	*Galium saxatile*	II(1-3)	*Potentilla erecta*	I(1-2)	*Potentilla erecta*	I(1)
Galium saxatile	I(1)	*Erica cinerea*	I(1-3)	*Erica tetralix*	I(1-2)	*Calluna vulgaris*	I(3)
Erica cinerea	I(1-3)	*Potentilla erecta*	I(1-2)	*Erica cinerea*	I(3)	*Erica tetralix*	I(2)
Blechnum spicant	I(3)	*Polytrichum commune*	I(2)	*Juncus spp.*	I(3)		
		Ulex spp.	I(3)	*Polygala serpyllifolia*	I(1)		
		Blechnum spicant	I(2)				
n	38		45		60		8

Species frequencies: I = 1-20%, II = 21-40%, III = 41-60%, IV = 61-80%, V = 81-100% occurrence

Species abundance (between brackets): 1 = 1-5%, 2 = 6-25%, 3 = 26-50%, 4 = 51-75%, 5 = 76-100% cover

Although six years had elapsed between the two observations (the air photo was taken in 1992, and the field survey was carried out in 1998), it was expected that results of the comparison could be useful worthwhile.

The BG group shows the highest frequency and abundance of all groups. The HG group shows the highest frequency of *Calluna* and ericaceous species whereas the SG group has a very low frequency of heathy species. *E. cinerea* is completely absent in the latter. Both *Agrostis* species (*Agrostis capillaris* and *curtisii*) are known to increase with a decline of *Calluna*, reflecting an increase in grazing pressure. From Table 7.5 it can be derived, that *Agrostis capillaris* has a higher frequency in both the BG and SG groups in comparison to the HG and GG classes. This corresponds well with the definitions based on the air photos described in Section 7.2.3. However, *Festuca ovina* shows a poor correspondence with the different vegetation groups. The increase of this species could normally be expected from the association with at least some grazing. This is not reflected in the frequency and abundance data from the table.

From the results, it could be concluded that there is a reasonable correspondence between the air photo groups at the catchment scale and species at plot scale within the TDR grid. Obviously, the degree of detail of the air photos is limited in comparison to the observations at the plot scale, but it could be a useful tool in distinguishing between vegetation communities.

Given the fact that air photos could be used to aid management at the catchment scale, give a reasonable reflection of vegetation at the plot scale, and also correspond reasonably with the TWINSPAN groups, it was decided that the air photo approach had many merits and therefore the air photo vegetation classes form the basis of subsequent analyses.

7.3 Soil properties and vegetation

In order to analyse the interaction between soils and vegetation, the statistical relationships between the different vegetation descriptions and soil properties (saturated hydraulic conductivity, bulk density, porosity and organic matter content) are analysed in this section. Section 7.3.1 describes the relationship of soil properties to individual plant species, and Section 7.3.2 discusses the relationships between the soil properties and the air photo classes. As it has been shown in Chapter 6 that soil moisture is an important control on the hydrology at the hillslope scale, the influence of this soil property is addressed separately in Section 7.4.

7.3.1 Soil properties in relation to individual vegetation species

Saturated soil hydraulic conductivities were related to individual vegetation species to determine whether soil hydrology was affected by vegetation. It was demonstrated (Table

7.2) that in the upper 10 cm of the soil, the percentage cover of *Molinia caerulea* showed a negative correlation and *Calluna vulgaris* and *Vaccinium myrtillus* positive correlations with the saturated hydraulic conductivity. However, between 10 and 20 cm depth, this effect was less for *Vaccinium myrtillus* and was non-significant for *Calluna vulgaris*. This is possibly due to the limited rooting depth of *Calluna*, which is dependent on the depth of the organic horizons (Rutter, 1955). At this depth, species like *Molinia caerulea, Carex spp.* and *Erica tetralix* showed a significant negative correlation with K_{sat}, whereas *Pteridium aquilinum* and *Agrostis capillaris* showed a positive correlation (Table 7.2).

During the K_{sat} sampling, field observations have shown that *Pteridium aquilinum* roots were mainly found at around 20 cm depth, which could have an important effect on the saturated hydraulic conductivity. However, bracken rhizomes mainly grow in horizontal direction (Williams *et al.*, 1987) and may therefore have a limited effect on the (vertical) conductivity (Arnett, 1974; Section 6.3.5). A Kruskal-Wallis test was used to test whether there was a significant difference between K_{sat} on locations with and without specific species and showed similar results of the effects of vegetation on K_{sat} (Table 7.3) to the correlation analysis. However, it also showed that *V. myrtillus* and *P. aquilinum* both had a positive effect on the conductivity throughout the top 20 cm.

Both analyses showed that *Molinia caerulea* and *Carex spp.* had a positive effect on soil porosity in the top 10 and 20 cm, respectively. However, these species were shown to be negatively correlated with saturated hydraulic conductivity. This could be attributed to the difference in sampling depth, as K_{sat} measurements were carried out over a depth of 10 cm, whereas porosity measurements were carried out on two samples 3 cm in thickness within the same soil layer, leaving 4 cm unsampled. Also, as stated previously, K_{sat} was only measured vertically, whereas total porosity does not give any information about spatial distribution or orientation of pores.

Other species (*Potentilla erecta, Erica tetralix*) also showed a similar, but less distinct difference in porosity between presence and absence. *A. capillaris*, *V. myrtillus*, *C. vulgaris* and *G. Saxatile* showed a decrease when present, depending on depth.

Virtually no relationships were found between transmission pores and individual plant species. Only bracken showed a positive effect, deeper than 4 cm in the topsoil (Table 7.1). It is very likely, that the percentage of transmission pores is a reflection of the vegetation community as a whole, instead of single species, both past and present.

Table 7.2: Spearman ranked correlation matrix between vegetation coverage and soil properties.

		Molinia caerulea	*Agrostis capillaris*	*Agrostis curtisii*	*Festuca ovina*	*Carex spp.*	*Galium saxatile*	*Potentilla erecta*	*Calluna vulgaris*	*Erica tetralix*	*Vaccinium myrtillus*	*Sphagnum spp.*	*Pteridium aquilinum*
$K_{sat\ 0-10}$	r_s	-0.42	-0.08	0.12	0.22	-0.23	-0.09	-0.13	0.47	-0.07	0.43	0.13	0.20
	p	0.086	0.729	0.628	0.373	0.345	0.700	0.588	0.052	0.771	0.074	0.601	0.400
$K_{sat\ 10-}$	r_s	-0.64	0.59	-0.05	0.32	-0.51	0.52	-0.10	-0.21	-0.41	0.29	0.06	0.58
	p	0.008	0.015	0.833	0.194	0.036	0.032	0.666	0.389	0.089	0.239	0.797	0.016
Φ_{0-3}	r_s	0.58	-0.70	-0.08	-0.26	0.65	-0.39	-0.19	0.25	0.48	-0.04	0.32	-0.29
	p	0.016	0.004	0.753	0.281	0.008	0.112	0.444	0.294	0.047	0.881	0.181	0.227
Φ_{4-7}	r_s	0.50	-0.51	0.11	-0.35	0.46	-0.43	0.36	0.11	0.24	-0.42	0.16	-0.18
	p	0.038	0.035	0.654	0.149	0.058	0.075	0.138	0.639	0.318	0.086	0.522	0.452
Φ_{12-15}	r_s	0.29	-0.13	0.03	-0.23	0.50	-0.29	-0.23	-0.36	-0.13	-0.36	0.41	0.05
	p	0.226	0.585	0.904	0.334	0.038	0.235	0.333	0.137	0.594	0.133	0.088	0.822
Φ_{16-19}	r_s	0.22	-0.02	0.16	-0.36	0.54	-0.20	-0.06	-0.35	-0.13	-0.47	0.34	-0.05
	p	0.358	0.928	0.515	0.140	0.026	0.413	0.795	0.146	0.587	0.053	0.162	0.840
ρ_{0-3}	r_s	-0.47	0.78	-0.04	0.18	-0.24	0.50	-0.07	-0.48	-0.52	-0.04	-0.31	0.34
	p	0.051	0.001	0.872	0.459	0.316	0.041	0.785	0.049	0.033	0.878	0.200	0.166
ρ_{4-7}	r_s	-0.57	0.30	0.11	0.27	-0.38	0.42	-0.23	0.09	-0.07	0.36	-0.13	0.18
	p	0.019	0.211	0.638	0.261	0.119	0.082	0.351	0.697	0.760	0.139	0.580	0.466
ρ_{12-15}	r_s	-0.34	0.15	0.08	0.21	-0.59	0.26	0.32	0.33	0.09	0.37	-0.38	-0.03
	p	0.163	0.542	0.730	0.376	0.015	0.287	0.188	0.174	0.723	0.126	0.118	0.892
ρ_{16-19}	r_s	-0.20	0.04	-0.21	0.40	-0.54	0.20	-0.03	0.29	0.10	0.49	-0.29	0.13
	p	0.408	0.870	0.384	0.097	0.026	0.413	0.905	0.238	0.687	0.044	0.237	0.579
om_{0-3}	r_s	0.06	-0.31	-0.15	-0.16	0.06	-0.31	0.04	0.14	0.17	-0.12	0.44	-0.06
	p	0.798	0.199	0.536	0.512	0.813	0.196	0.857	0.574	0.494	0.632	0.070	0.814
om_{4-7}	r_s	0.30	-0.23	-0.27	-0.18	0.42	-0.24	0.17	-0.11	-0.01	-0.23	0.40	-0.11
	p	0.214	0.346	0.270	0.465	0.081	0.315	0.492	0.656	0.954	0.343	0.100	0.642
om_{12-}	r_s	0.35	-0.33	0.09	-0.41	0.53	-0.36	-0.13	-0.09	0.05	-0.48	0.25	-0.10
	p	0.146	0.169	0.720	0.091	0.029	0.134	0.594	0.718	0.850	0.047	0.306	0.690
om_{16-}	r_s	0.33	-0.17	0.20	-0.35	0.50	-0.25	-0.09	-0.23	-0.04	-0.38	0.32	-0.08
	p	0.173	0.489	0.419	0.144	0.038	0.306	0.722	0.346	0.869	0.118	0.185	0.746
$\Phi_{t\ 0-3}$	r_s	-0.29	0.50	0.00	-0.25	-0.30	0.22	-0.43	-0.33	-0.19	-0.12	-0.12	0.02
	p	0.186	0.022	0.987	0.261	0.168	0.309	0.047	0.134	0.382	0.598	0.576	0.928
$\Phi_{t\ 4-7}$	r_s	-0.02	-0.22	0.21	0.16	0.02	0.04	-0.12	0.32	-0.02	0.00	-0.46	0.47
	p	0.944	0.316	0.335	0.464	0.917	0.853	0.576	0.141	0.930	0.996	0.835	0.032
$\Phi_{t\ 12-15}$	r_s	0.02	0.00	0.27	0.07	0.12	0.10	0.01	0.04	-0.41	0.06	-0.18	0.41
	p	0.938	0.995	0.233	0.762	0.580	0.656	0.950	0.859	0.036	0.776	0.424	0.066
$\Phi_{t\ 16-19}$	r_s	0.07	-0.04	0.09	0.01	0.25	0.15	-0.24	-0.05	-0.20	0.05	0.11	0.37
	p	0.752	0.865	0.678	0.954	0.256	0.500	0.275	0.834	0.382	0.820	0.637	0.100

$n = 18$, $p < 0.10$,

ρ: dry bulk density (g cm^{-3}), Φ: total porosity ($cm^3\ cm^{-3}$), Φ_t: transmission pores ($cm^3\ cm^{-3}$)

om: organic matter content (LOI, g $100g^{-1}$)

Boxed values are significant

Table 7.3: Kruskal-Wallis test between soil properties and species present or absent.

		Molinia caerulea	Agrostis capillaris	Agrostis curtisii	Festuca ovina	Carex spp.	Galium saxatile	Potentilla erecta	Calluna vulgaris	Erica tetralix	Vacciniu m myrtillus	Sphagnu m spp.	Pteridium aquilinum
$K_{sat\ 0\text{-}10}$	T_{KW}	1.37	0.73	0.30	0.39	0.83	0.68	0.05	7.67	0.06	3.67	1.52	2.94
	+/-	-	-	+	+	-	-	-	+	-	+	+	+
	p	0.242	0.391	0.585	0.533	0.363	0.411	0.825	0.006	0.805	0.055	0.217	0.086
$K_{sat\ 10\text{-}20}$	T_{KW}	5.94	6.61	0.59	1.92	4.63	1.47	1.67	1.53	3.49	3.67	1.52	4.73
	+/-	-	+	-	+	-	+	-	-	-	+	+	+
	p	0.015	0.010	0.443	0.166	0.031	0.225	0.196	0.217	0.062	0.055	0.217	0.030
$\Phi_{0\text{-}3}$	T_{KW}	5.31	6.96	0.13	0.59	7.43	3.68	0.08	1.92	5.25	0.27	0.03	0.48
	+/-	+	-	-	-	+	-	+	+	+	-	+	-
	p	0.021	0.008	0.713	0.108	0.006	0.055	0.784	0.166	0.022	0.606	0.860	0.491
$\Phi_{4\text{-}7}$	T_{KW}	2.90	3.17	0.09	0.48	3.13	2.33	2.84	0.04	1.04	3.13	0.78	0.67
	+/-	+	-	-	-	+	-	+	-	+	-	-	-
	p	0.089	0.075	0.764	0.491	0.077	0.127	0.092	0.843	0.307	0.077	0.378	0.412
$\Phi_{12\text{-}15}$	T_{KW}	0.18	0.12	0.61	0.60	4.45	1.57	0.13	1.64	0.00	1.55	1.25	0.60
	+/-	+	-	+	-	+	-	-	-		-	+	+
	p	0.670	0.725	0.434	0.439	0.035	0.210	0.720	0.201	1.000	0.213	0.263	0.439
$\Phi_{16\text{-}19}$	T_{KW}	0.02	0.18	1.14	1.43	4.45	0.11	0.11	3.55	0.02	4.75	1.02	0.05
	+/-	+	-	+	-	+	-	-	-	-	-	+	-
	p	0.887	0.670	0.286	0.231	0.035	0.744	0.741	0.060	0.881	0.029	0.312	0.831
$\Phi_{t\ 0\text{-}3}$	T_{KW}	3.13	4.73	0.09	0.39	1.92	1.22	5.92	2.50	0.78	0.00	0.03	0.00
	+/-	-	+	-	-	-	+	-	-	-	+	-	-
	p	0.077	0.030	0.764	0.533	0.165	0.268	0.015	0.114	0.378	0.969	0.860	0.947
$\Phi_{t\ 4\text{-}7}$	T_{KW}	0.19	1.57	0.25	0.79	0.02	0.00	0.05	0.98	0.00	1.67	0.01	2.72
	+/-	+	-	+	+	+		+	+	+	+	-	+
	p	0.664	0.210	0.616	0.375	0.886	1.000	0.825	0.323	0.972	0.196	0.916	0.099
$\Phi_{t\ 12\text{-}15}$	T_{KW}	0.13	0.18	0.26	0.51	0.49	0.13	0.00	0.00	2.93	0.22	0.03	0.97
	+/-	+	+	+	+	+	+			-	+	-	+
	p	0.722	0.670	0.612	0.477	0.482	0.720	1.000	1.000	0.087	0.640	0.869	0.324
$\Phi_{t\ 16\text{-}19}$	T_{KW}	0.08	0.05	0.08	0.61	1.22	0.29	0.15	0.13	0.73	0.30	0.87	0.97
	+/-	+	+	-	+	+	+	-	-	-	+	+	+
	p	0.776	0.831	0.772	0.434	0.269	0.591	0.697	0.722	0.392	0.586	0.350	0.324
$\rho_{0\text{-}3}$	T_{KW}	2.26	8.04	0.05	0.13	0.51	5.71	1.29	4.18	4.04	0.05	0.10	0.31
	+/-	-	+	-	+	-	+	-	-	-	+	-	+
	p	0.133	0.005	0.815	0.718	0.473	0.017	0.256	0.041	0.045	0.825	0.751	0.577
$\rho_{4\text{-}7}$	T_{KW}	2.06	0.43	0.01	0.24	1.92	1.88	0.12	0.63	0.10	3.67	0.15	1.04
	+/-	-	+	+	+	-	+	-	+	-	+	+	+
	p	0.151	0.510	0.920	0.622	0.165	0.170	0.724	0.429	0.751	0.055	0.698	0.309
$\rho_{12\text{-}15}$	T_{KW}	0.32	0.12	0.32	0.71	5.82	1.16	0.29	1.29	0.01	2.19	0.56	0.24
	+/-	-	+	-	+	-	+	+	+	-	+	-	-
	p	0.357	0.725	0.570	0.398	0.016	0.282	0.591	0.256	0.941	0.139	0.456	0.622
$\rho_{16\text{-}19}$	T_{KW}	0.02	0.13	1.82	1.43	4.45	0.11	0.03	2.77	0.02	5.45	0.61	0.51
	+/-	-	-	-	+	-	+	+	+	+	+	-	+
	p	0.887	0.722	0.177	0.231	0.035	0.741	0.869	0.096	0.881	0.020	0.436	0.477
$om_{0\text{-}3}$	T_{KW}	0.48	0.03	0.10	0.00	0.13	0.94	1.59	0.06	0.04	0.18	3.75	0.03
	+/-	-	+	+	-	-	-	-	-	+	+	+	+
	p	0.488	0.852	0.753	0.951	0.715	0.333	0.208	0.804	0.841	0.674	0.053	0.854
$om_{4\text{-}7}$	T_{KW}	0.78	0.47	0.02	0.24	3.33	0.56	0.00	0.25	0.00	1.59	0.36	0.31
	+/-	+	-	-	-	+	-	+	-	+	-	+	-
	p	0.378	0.495	0.900	0.622	0.068	0.456	0.944	0.620	0.947	0.208	0.548	0.580
$om_{12\text{-}15}$	T_{KW}	0.94	0.21	0.49	0.72	4.63	0.96	0.26	1.21	0.91	4.26	1.04	0.98
	+/-	+	-	+	-	+	-	-	-	+	-	+	-
	p	0.339	0.644	0.483	0.099	0.031	0.327	0.611	0.271	0.341	0.039	0.307	0.323
$om_{16\text{-}19}$	T_{KW}	0.40	0.00	0.70	1.41	4.63	0.96	0.08	1.70	0.03	4.57	1.19	0.11
	+/-	+		+	-	+	-	-	-	+	-	+	-
	p	0.526	1.000	0.404	0.235	0.031	0.327	0.784	0.193	0.860	0.033	0.275	0.742

n = 22, p < 0.10 instead of p < 0.05 due to limited sample size
Boxed values are significant

M. caerulea showed a negative correlation with bulk density. However, no difference was found in bulk density values with and without a cover of *Molinia*. *Calluna* and *E. tetralix* also showed a decrease in bulk density with increasing cover, but this was only significant in the topsoil, and in the case of *Calluna* this effect was opposite between 16 and 19 cm depth.

As was shown in this section, the relationship between individual plant species on soil properties is very complex. Many different soil properties determine the occurrence of species, but species also have their effect on the soil. Because of the complexity between the different soil characteristics and the vegetation communities, simple correlations often give unclear or conflicting results. In order to obtain a clearer overview, the correlations between soil properties are analysed statistically between the air photo vegetation groups in the following section.

7.3.2 The relationship between soil properties and air photo vegetation groups

All 23 sample points in the TDR grid were sorted into the four vegetation classes following the classification based on air photos. The main aim was to describe the relationships statistically. Possible reasons for the differences between groups are discussed in the next chapter.

The largest group consisted of the Bracken and Grass-class (BG), with nine sample points in total, whereas the Short Grass-class (SG) only consisted of two samples. A Kruskal-Wallis test was carried out to investigate the difference in soil properties under different vegetation classes, in order to compare this with the results from the effect of individual species on soil properties and to extrapolate findings to the hillslope and catchment scale (Table 7.4).

It was shown that bulk densities were higher within the SG and BG classes (0.32 g cm^{-3}) near the soil surface than under Gorse and Grass (GG) and the Heather/Grass mosaic (HG) (0.18 g cm^{-3}), which was significant despite the small sample size of the SG-class. This effect was only significant in the upper 3 cm of the soil and decreased with depth. Consequently, porosity values were highest in the heather/grass mosaic and gorse and grass-classes and were significant at 0-3 and 4-7 cm depth, the difference decreasing with depth. This was also reflected within the organic matter contents of the different vegetation classes (Table 7.4), showing that the effect of vegetation on the soil reaches only shallow depths in moorland communities.

Table 7.4: Kruskal-Wallis test between air photo vegetation class and soil properties.

Vegetation group	HG	GG	BG	SG	T_{KW}	p	average	stdev
n	7	5	9	2				
$K_{sat\ 0\text{-}10}$	61.1	28.6	47.3	37.1	4.27	0.23	46.5	34.2
$K_{sat\ 10\text{-}20}$	20.9	11.0	45.1	22.2	5.74	0.12	27.6	31.6
$\Phi_{0\text{-}3}$	0.915	0.931	0.876	0.882	7.59	0.06	0.900	0.041
$\Phi_{4\text{-}7}$	0.875	0.911	0.841	0.771	9.47	0.02	0.860	0.056
$\Phi_{12\text{-}15}$	0.782	0.820	0.728	0.693	2.05	0.56	0.765	0.121
$\Phi_{16\text{-}19}$	0.730	0.761	0.692	0.628	1.36	0.71	0.712	0.145
Volume % of $\Phi_{trans,\ 0\text{-}3}$	32.2	29.9	24.1	29.2	2.94	0.40	28.10	10.0
Volume % of $\Phi_{trans,\ 4\text{-}7}$	20.3	24.1	29.1	31.9	5.56	0.13	25.80	7.4
Volume % of $\Phi_{trans,\ 12\text{-}15}$	23.6	21.6	33.2	35.8	7.39	0.07	27.47	8.9
Volume % of $\Phi_{trans,\ 16\text{-}19}$	26.9	25.6	28.1	33.1	1.51	0.65	27.69	8.1
$\rho_{0\text{-}3}$	0.18	0.19	0.3	0.34	9.77	0.02	0.25	0.10
$\rho_{4\text{-}7}$	0.31	0.26	0.37	0.57	5.44	0.14	0.35	0.13
$\rho_{12\text{-}15}$	0.58	0.45	0.72	0.76	2.53	0.47	0.61	0.31
$\rho_{16\text{-}19}$	0.70	0.62	0.82	0.97	1.81	0.61	0.76	0.39
$om_{0\text{-}3}$	86.3	76.9	77.4	55.1	6.16	0.10	78.1	14.4
$om_{4\text{-}7}$	72.7	67	57.4	33	6.76	0.08	62.0	18.4
$om_{12\text{-}15}$	55.4	43.7	32.6	16.4	3.73	0.29	40.9	27.3
$om_{16\text{-}19}$	33.8	32.3	18.6	11.9	2.69	0.44	25.9	24.4
slope	7.4	6.4	7.6	14.0	3.58	0.31	7.8	4.3

n = 23, p < 0.10. Values indicated in grey are not significant.

ρ: dry bulk density (g cm^{-3}), Φ: porosity(cm^3 cm^{-3}), Φ_{trans}: transmission pores (volume % of the total porosity)

om: organic matter content (LOI, g 100g^{-1})

7.4 Soil moisture – vegetation relationships

Because in Chapter 6, the importance of soil moisture to the hydrology on the hillslope was demonstrated, this section analyses the relationship between vegetation and soil moisture separately at the wider scale. Therefore, air photo vegetation groups were used to analyse differences. Results are shown in Table 7.5.

Within the soil-sampling grid, the 23 sampling points were used to be able to compare to the results from the previous section. Average, maximum and minimum soil moisture contents were not significantly different between vegetation groups. However, there seems to be a tendency towards drier soils especially under the short grass group, but due to the small number of samples, the difference is not significant. When taking the full data set (n = 151) into account, a significant difference in moisture contents between groups could be distinguished.

Table 7.5: Kruskal-Wallis test between vegetation groups and soil moisture within the sample data set and the full TDR data set.

Veg	23 sample points TDR-grid						151 points TDR-grid						1977 points hillslope experiment			
	θ_{min}	θ_{mean} (cm^3 cm^{-3})	θ_{max}	slope (°)	ti*	n (-)	θ_{min}	θ_{mean} (cm^3 cm^{-3})	θ_{max}	slope (°)	ti* (-)	n	θ_{thetap}	slope (°)	ti* (-)	n
HG	0.36	0.61	0.71	7.4	7.0	7	0.37	0.59	0.67	9.6	6.9	38	0.67	10.0	7.2	283
GG	0.41	0.65	0.75	6.4	9.6	5	0.37	0.58	0.66	9.3	7.1	45	0.69	9.5	7.6	556
BG	0.39	0.59	0.69	7.6	7.1	9	0.42	0.59	0.68	8.9	7.3	60	0.69	9.1	7.6	1052
SG	0.34	0.54	0.61	14.0	7.0	2	0.32	0.55	0.62	16.0	7.1	8	0.71	11.6	7.5	79
T_{KW}	1.68	1.38	4.22	3.58	1.17		12.3	10.2	14.0	21.7	11.22		38.8	31.5	81.2	
p	0.642	0.710	0.239	0.311	0.750		0.007	0.017	0.003	0.000	0.012		0.000	0.000	0.000	

**Topographic index*

It was expected that short grass (with or without bracken) is probably wetter due to higher bulk density, lower porosity and lower organic matter contents (Section 7.3.1). While the BG-class confirmed this expectation, SG showed the opposite. The local slope angle however, is shown to be significantly higher within this group, and as shown previously, this implies naturally lower soil moisture contents due to increased drainage. Local topography probably is a more important factor in influencing the soil moisture than vegetation. Therefore, these two groups are not easily comparable.

To validate the findings at the hillslope scale, soil moisture measurements of the top 6 cm of the soil made across the whole hillslope were compared to their air photo vegetation class, slope and topographic index values (Section 4.3.4). Table 7.5 shows the results, from which it was clear that the SG vegetation group is significantly wetter. It also showed that slope angles were higher within this class. When comparing the topographic index values, it was shown that under the HG group, values were was significantly lower.

This could indicate that under the short grass group (SG), soil moisture values are significantly higher under similar topographic conditions, whereas under the semi-natural heather vegetation, soil moisture contents are slightly lower. However, this could not be fully explored, as soil moisture under different vegetation types or topographic conditions could not be studied separately. A further exploration of the difference between vegetation groups and the implications of these findings are discussed in the next chapter.

7.5 Soil moisture as explained by topography and vegetation

Chapter 6 demonstrated the importance of soil moisture to the hydrology at the hillslope scale. It was also suggested in that chapter that topography and vegetation might have an important influence on the spatial organisation of soil moisture. In Section 6.7, two different wetness states were introduced following (Grayson *et al.*, 1997). In the 'dry' state, it was suggested that soil moisture patterns are determined mainly at a local scale, among others by vegetation. Evaporation, transpiration and interception by cover and leaf litter are important factors, which in turn depend on the vegetation type. During 'wet' periods, topography becomes more important, and the influence of lateral (soil) water movement on soil moisture patterns increases. The moisture mosaic is determined by non-local controls.

Previous sections in this chapter demonstrated the statistical difference in soil moisture under different topographic conditions and under different vegetation groups. In this section, a multiple regression analysis was used as a tool to establish a possible explanation of the soil moisture content, in order to achieve an understanding of the factors controlling soil moisture.

For the analysis, the 23 sample points of the TDR grid were chosen because of the detailed vegetation information that was available for these locations on the hillslope. In the regression equation, variables used to explain moisture contents were slope angle, topographic index, altitude above the stream and the presence/absence of individual plant species (based on the 20x20 cm quadrats). Although slope angle and the topographic index were expected to be interrelated, no autocorrelation was found during the analysis, and therefore the two variables could be treated separately. A reason for the absence of the autocorrelation could be that the slope values were measured in the field, but slope angles used in the topographic index were derived from a DEM (Section 4.6.1). During trials, it was found that the occurrence of species was more important than the actual percentage cover. Therefore, only the presence/absence of the individual species was used.

As it was shown that soil moisture contents were highly dependent on the wetness states, the dataset was split into two separate sets. The sets represented the dry and wet conditions, following the definitions of Chapter 6.

For each set, soil moisture contents were averaged at each location (14 and 5 occasions for the dry and wet state, respectively). Errors in the average due to missing values, especially on the wettest and driest occasions were analysed and total means without missing data values were between 0.00 and 0.02 $cm^3\ cm^{-3}$ off the total average. Due to this small error, within the same range as TDR-measurements in organic soils (Roth *et al.*, 1992) no reason was found to eliminate TDR-locations from the analysis with missing data and therefore all data points could be used.

Single independent variables were excluded when $p > 0.05$. The following regression models were found:

[7.1] $\theta_{average,\,dry} = (66.6 - 0.42\,\beta + 1.20\,Inatanb - 5.25\,Ac - 11.67\,Vm - 7.69\,Cv) \times 10^{-2}$

[7.2] $\theta_{average,\,wet} = (88.98 - 1.04\,\beta - 0.11\,z - 4.50\,Ac - 11.95\,Vm) \times 10^{-2}$

where:

$\theta_{average}$ = mean soil moisture content ($cm^3\ cm^{-3}$);

β = slope angle (°);

$Inatan\beta$ = topographic index (Quinn *et al.*, 1991);

z = altitude above stream (m);

Ac = occurrence of *Agrostis capillaris* (1 = present, 0 = absent);

Vm = occurrence of *Vaccinium myrtillus* (1 = present, 0 = absent);

Cv = occurrence of *Calluna vulgaris* (1 = present, 0 = absent).

The regression analyses showed that in general, soil moisture content increases with absence of *Agrostis capillaris*, *Calluna vulgaris* and *Vaccinium myrtillus*. Although this seems to contradict the fact that these species (especially *Calluna*) are associated with wetter areas (Stace, 1997), this is only the case in general terms. Vegetation is partly determined by soil wetness, and therefore the vegetation type will only occur in favourable areas. However, these favourable areas are suitable over a relatively long period, *i.e.* at an annual time scale. The influence of the vegetation in terms of evaporation, transpiration and interception on soil moisture fluctuates at a much shorter time scale.

As can be expected, soil moisture increases with increasing topographic index (Quinn *et al.*, 1991) and decreases with slope angle (Dunne, 1978; Black, 1991) and altitude in both equations. The predictive value of the regression equation was high, with an R^2_{adj} of 0.84 and 0.82 for the equations 7.1 and 7.2, respectively. The p-value of both models was 0.0000 (n = 23), indicating a highly significant relationship.

This analysis shows that in terms of soil moisture content, the slope angle and related the topographic index are important. It was shown that in the dry state, the soil water status could generally be explained more by vegetation cover than by topographic features than in the wet state. During wet conditions, the slope factor was a much larger influence, and the effects of *Agrostis capillaris* and *Calluna* were less and not significant, respectively. The interception of the different plant species might also have its effect on the soil moisture contents, but was not taken into account. The complexity of this variable is discussed in Section 5.5.

To further test the relative importance of both the local and non-local controls on the variation in soil moisture, all vegetation variables were removed from the dry state analysis. As a result, the R^2_{adj} value decreased dramatically from 0.84 to around 0.48 (p =

0.001). Conversely, when only the topographic variables were removed, the amount of explained variation only decreased down to 0.73 ($p = 0.000$), indicating that vegetation, the local control, is a more important factor in explaining the variation than the non-local controls.

When the vegetation variables were removed from the wet state analysis, the R^2_{adj} also decreased significantly, from 0.82 to 0.58 ($p = 0.000$), implying that vegetation is important. This reduction in explained variation was less dramatic than in the dry state analysis however. When the topographic variables were dropped, the R^2_{adj} value was also dramatically reduced, to 0.48 ($p = 0.001$), suggesting the relative importance of topographic factors in the wet state.

It could therefore be concluded that during dry conditions, soil moisture is more influenced by the local vegetation than by topographic characteristics. In the wet state, the topographic controls become more important. These results are comparable as the results reported by Grayson *et al.* (1997) and Western *et al.* (1999).

The same analysis was carried out with all 151 points of the TDR grid. Species with presence at only one location (*e.g. Juncus spp.*, *Ulex spp.*) were left out. The following regression models were established:

[7.3] $$\theta_{average,\,dry} = (56.80 - 0.46\,\beta + 1.22\,ln a tan\beta - 0.07\,z + 1.93\,Cs - 3.02\,Pa - 2.25\,Ac) \times 10^{-2}$$

[7.4] $$\theta_{average,\,wet} = (68.61 - 0.75\,\beta + 1.11\,ln a tan\beta - 0.09\,z + 1.90\,Cs - 2.97\,Pa - 1.73\,Ss) \times 10^{-2}$$

where:

$\theta_{average}$ = mean soil moisture content ($cm^3\ cm^{-3}$);

β = slope angle (°);

$ln a tan\beta$ = topographic index;

z = altitude above stream (m);

Cs = occurrence of *Carex Spp.* (1 = present, 0 = absent);

Pa = occurrence of *Pteridium aquilinum* (1 = present, 0 = absent);

Ac = occurrence of *Agrostis capillaris* (1 = present, 0 = absent);

Ss = occurrence of *Sphagnum spp.* (1 = present, 0 = absent).

The predictive value of the models was much lower, with an R^2_{adj} value of 0.33 and 0.40 for the equations 7.3 and 7.4, respectively. This was thought to be mainly due to the larger area of vegetation coverage estimation (50 x 50 cm), as opposed to 20 x 20 cm in the 23 sample analysis. The smaller vegetation coverage sample size is a better reflection of the soil moisture content in the middle of the quadrat (Section 4.4.2), as it is closer to the sampling volume of the TDR measurements (Baker and Lascano, 1989).

Although the predictive value was significantly lower, the regression equations were still significant ($p = 0.000$). In this analysis, soil moisture content was explained by the same topographic variables, but vegetation species were partly different. *Pteridium aquilinum* was negatively correlated with soil moisture content, which was expected to reflect the nature of bracken growing in non-saturated conditions and the increased drainage due to its extensive root system. *Carex Spp.* were positively correlated to soil moisture contents. In dry conditions, soil moisture content increases with the absence of *Agrostis capillaris*, similar to the findings of the 23 sample analysis. In the wet state, soils are drier when *Sphagnum spp.* are present. This is highly unlikely, as *Sphagnum* mosses are normally associated with very high moisture levels. No explanation for this could be found.

There is a striking similarity in the influence of slope angle, altitude and topographic index on the soil moisture content between the 23 and 151 sample analysis, with constants both in the same order of magnitude.

Results presented here are of major importance to the understanding of factors determining soil moisture patterns in the study area. The explanation of local and non-local controls, proposed by Western *et al.* (1999) and Grayson *et al.* (1997), applied earlier in Chapter 6, fits well to the results presented in this thesis and can therefore be applied to the study area on Dartmoor.

7.6 Summary

In this chapter, the results of the vegetation distribution studies within the TDR grid and the entire catchment areas were presented and discussed. It was shown that heathy species are mainly found near the top of the slope, with invading bracken occurring locally. Further down the slope, vegetation was increasingly being characterised by more grassy vegetation, dominated by *Molinia* in places.

The results of the two different vegetation classifications were outlined. It was suggested, that resulting vegetation groups of the TWINSPAN and air photo classification were similar but not the same, and could therefore reasonably be compared. A combination of individual plant species at the plot scale and vegetation groups, defined by air photo classification at the catchment scale was shown to correspond sufficiently, and therefore the TWINSPAN classification was superfluous.

The relationship between vegetation and soil properties was therefore investigated in two ways: comparing soil properties to single vegetation species and to the air photo vegetation classes. The saturated conductivity was influenced most by the different types of vegetation species, but this depended greatly on depth. *Molinia* and *Carex spp.* showed a positive correlation with porosity. Only bracken showed a (positive) correlation to the volume of transmission pores. However, organic matter content and bulk density did not show any relationships to single species. Hence, one of the main conclusions was that the individual species effects on soil properties were too complex to distinguish. Therefore, the relationships determined between vegetation communities and the soil were found to be more appropriate.

The air photo class results showed increased porosity and subsequently decreased bulk density values in the HG (heathy species) group, but only in the uppermost topsoil. Organic matter content in the HG group in the top 10 cm was also significantly higher in the top 10 cm of the soil. Additionally, the volume of transmission pores was significantly different in the top 10 cm. Soil moisture contents were significantly different under different vegetation groups and under different topographic conditions.

A regression analysis confirmed vegetation and topography are important factors to explain soil moisture variation. The local and non-local controlling factors in different wetness states within the TDR-grid was demonstrated with the application of findings by Western *et al.* (1999) and Grayson *et al.* (1997) to the Dartmoor watershed.

Chapter 8: Land management

8.1 Introduction

The aim of this chapter is to assess the impact of land management on the soils and hydrology of the study area.

- In Section 8.2, the results of the vegetation classification at the catchment scale are explained to give a background on community distributions within the watershed. Also, the number and spatial distribution of animals in the summer season will be described and linked to both vegetation characteristics and MAFF (part of DEFRA since 2001) ESA grazing guidelines and are compared to results presented by various authors.
- Section 8.3 focuses on the impact of fire at the plot scale, presenting the results from the burning experiments. The burn will be compared with burns carried out by farmers in the same time period and is characterised by temperature, fuel load and the impact on soil moisture.
- In Section 8.4, causal-relationship diagrams are introduced to visualise the complex interrelations between vegetation and soil within the catchment system.
- Subsequently, Section 8.5 describes and explains the possible (causal) interactions between grazing pressures, vegetation changes and soil properties.
- Section 8.7 will than compile the implications of grazing and burning to the soil sand hydrology, followed by the proposal of a conceptual model of the moorland system, focussed on land management in Section 8.8.

8.2 Grazing patterns in the study area

8.2.1 Vegetation distributions at the catchment scale

Supervised air photo vegetation classification and field verification (Chapter 4) yielded various different vegetation classes as described in Section 7.2.3, but are repeated here for clarity:

- **HG**: Heather-grass mosaic, with *Calluna* and *Festuca ovina* as main species;
- **GG**: Gorse (*Ulex spp.*) and/or long grasses, mainly *Molinia caerulea*;
- **BG**: Predominantly *Pteridium aquilinum* with an underlying layer of short, mainly grazed grasses (*F. ovina* and *A. capillaris*);
- **SG**: Grasses with a very short sward height (*F. ovina* and *A. capillaris* mainly).

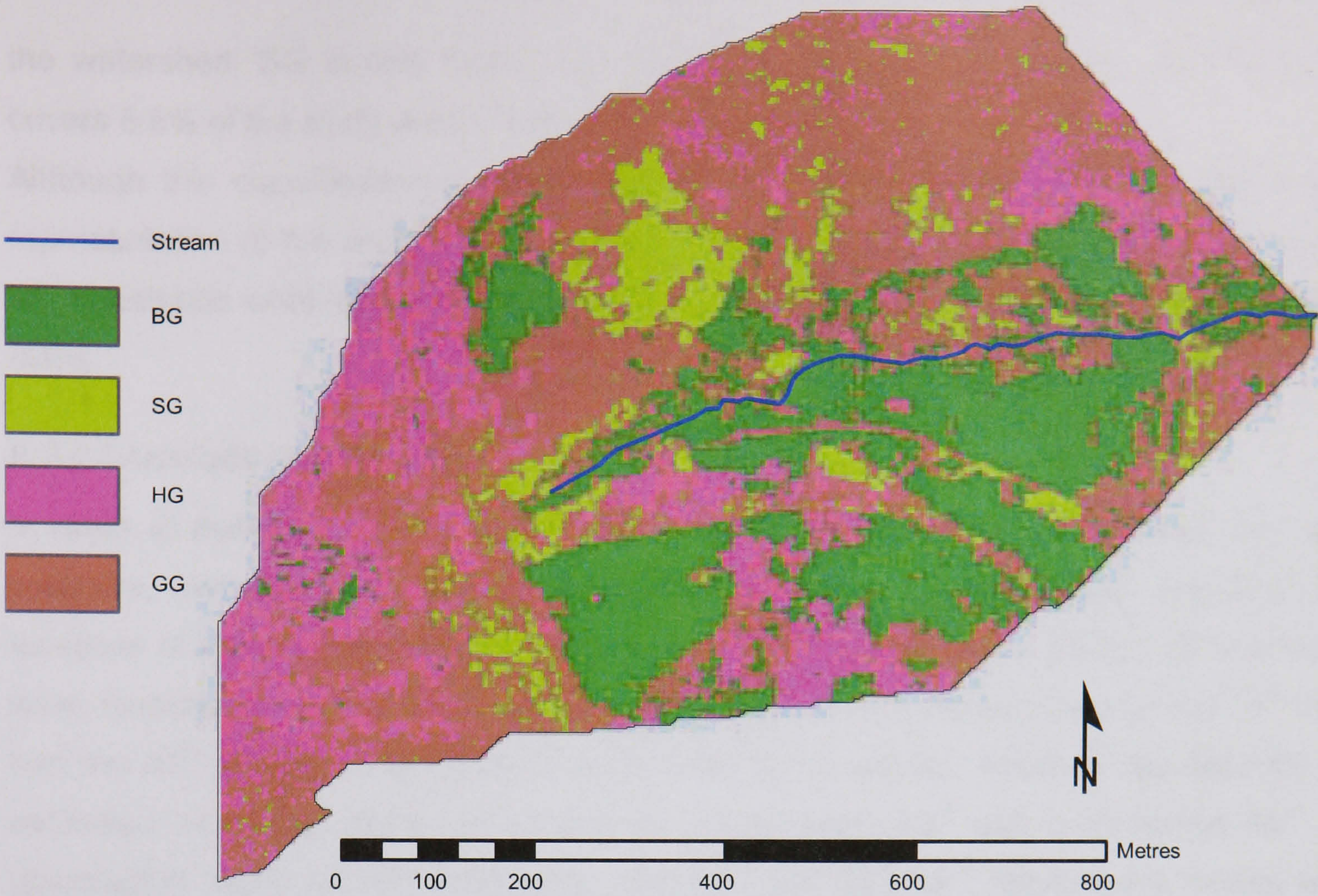


Figure 8.1: The distribution of the air photo vegetation classes within the catchment.

Table 8.1: Areas occupied by vegetation classes within the watershed.

Vegetation class	Vegetation code	Area (ha)	Area (%)
Bracken and grass	BG	15.3	24.7
Short grass	SG	4.0	6.6
Gorse and grass	GG	31.8	52.1
Heather/grass mosaic	HG	10.1	16.6
Total		61.0	100

The HG class covers 16.6% of the catchment area (Fig. 8.1), but is probably suppressed by heavy grazing in the area according to the Heather Utilisation Survey (HUS) classification by DNPA (2000, unpublished data). Its main extent is on the higher parts of the catchment.

The GG class is found mainly on the northern hillslopes and consists of low gorse only in the northern half of the catchment (up to 40 cm tall), together with heathy species and long grasses. In the rest of the catchment, the GG category mainly represents long grasses. The total class covers 52.1% of the watershed area.

The BG class consists mainly of bracken with an underlying layer of short to very short grasses, similar to the grasses in the SG category. The bracken is invading large areas of the study catchment as has been observed from air photos (Section 7.2). Its main extent is on the valley floor and the less sloping areas in the southeast. It covers about 24.7% of the watershed. SG is only found in a few distinctive places within the watershed and covers 6.6% of the study area (Table 8.1).

Although this classification is only a guideline for major communities, it gives a good representation of the vegetation at the watershed scale (Section 7.2.4). The next section will investigate whether there is a significant difference in grazing densities per vegetation class.

8.2.2 Livestock monitoring

In order to estimate grazing impacts on the soils and hydrology in the watershed, total numbers, densities and spatial distribution figures of livestock were required. The locations of individual livestock (sheep, cattle and ponies) within the study catchment area were recorded on a map on 15 separate occasions in the period between the 11th June and the 27th October 1999 (Section 4.7). Over all occasions, livestock densities for the catchment averaged at of 0.47 sheep ha^{-1}, 0.14 cattle ha^{-1} and 0.03 ponies ha^{-1} per observation. Maximum densities were 1.03, 0.70 and 0.23 ha^{-1}, respectively. Sheep were observed on 14 occasions, cattle ten times, but ponies were only observed during three observations.

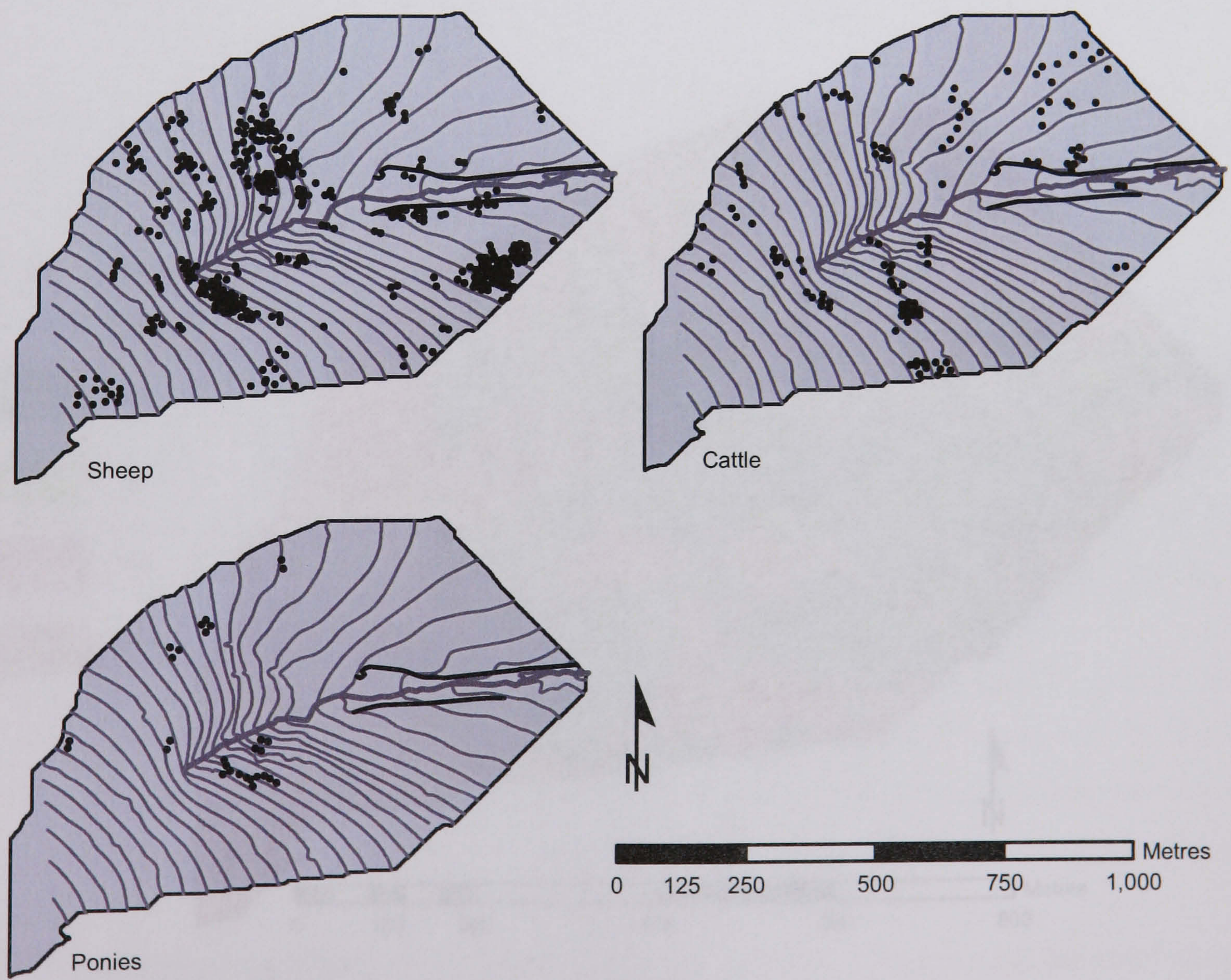


Figure 8.2: Livestock distributions combined over all 15 occasions. Points represent individual animals.

The map yielded a heterogeneous distribution (Fig. 8.2). Clearly, sheep are most abundant, and appear to be roaming in three distinct areas: In the southeast near the catchment divide, near the source area of the stream and in the low-gradient area between the two streams. Apart from one occasion (9th August), sheep were not recorded above 450 metres on the more exposed plateau. Sheep were seldom observed grazing individually.

Cattle show a more random grazing pattern, although the southeast and southwest seems to be avoided. Ponies were only observed occasionally in the area and seemed to prefer the higher altitudes in the northwestern part of the watershed. The lack of livestock in the southwest is most likely due to the exposed fringe of the high plateau.

As these observations were carried out in different weather conditions but in summer only, animal distributions are only representative for this period. In the past, livestock grazed on the moors throughout the year. Since the introduction of the Dartmoor ESA (MAFF, 1998), farmers are encouraged by supplementary subsidies to remove cattle from the moors in winter, and pony numbers are greatly reduced during this season (Goodfellow, 2000, pers. comm.; Chapter 3), so the effects of livestock on the vegetation and soils are currently expected to be greatest in summer.

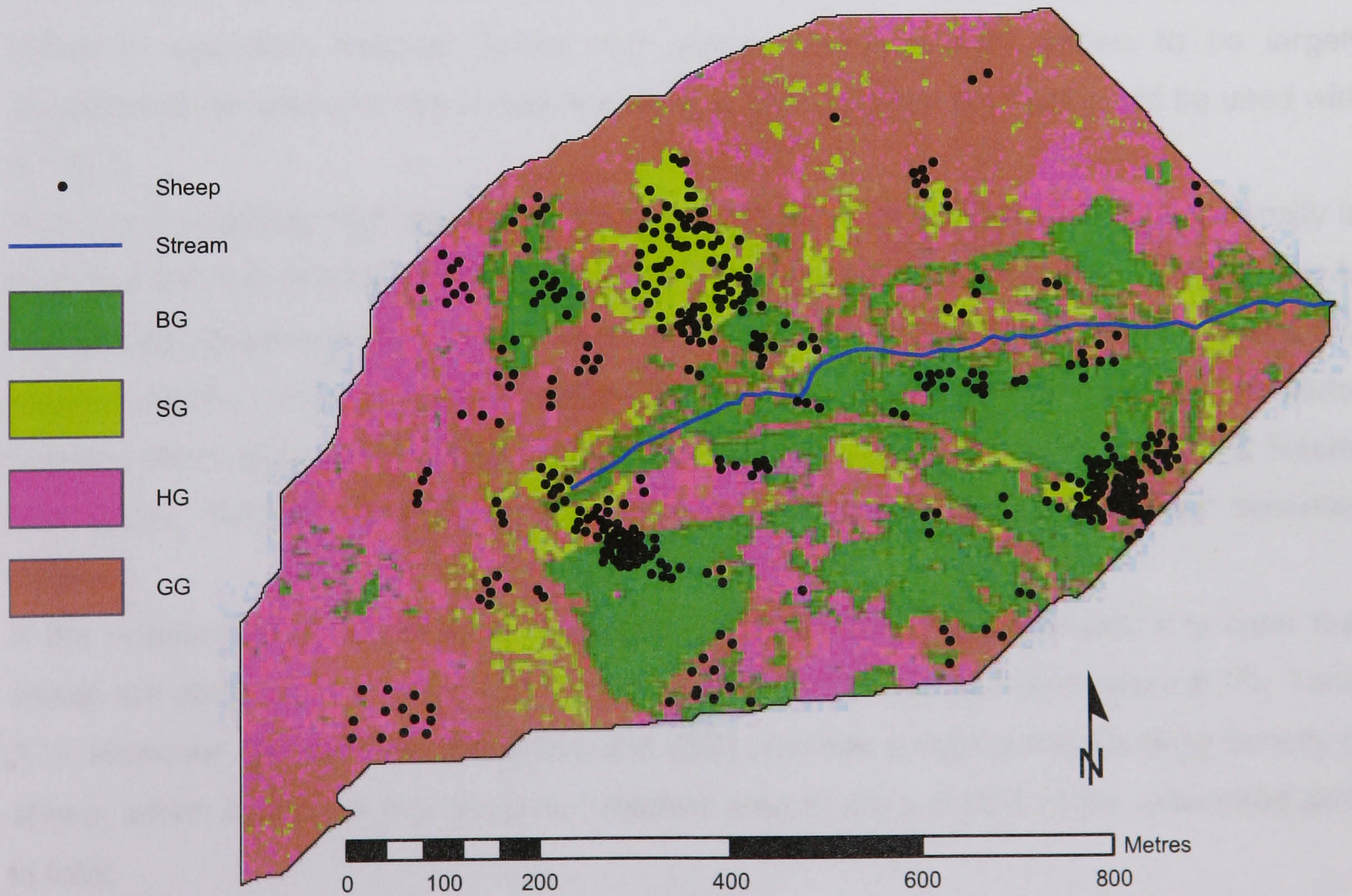


Figure 8.3: Sheep distribution and vegetation classes.

8.2.3 Vegetation as a reflection of grazing pressures

Livestock distributions were compared to the vegetation map in a GIS, in order to relate vegetation classes to different grazing pressures (Fig 8.3). Preferences of grazing behaviour were analysed using a Chi-square analysis on each individual species. This test is used to test the difference in frequencies between groups (Shaw and Wheeler, 1994). Livestock frequencies needed to be standardised for area. The main aim of these calculations was to compare livestock densities with the Dartmoor ESA requirements (MAFF, 1998). These requirements are at farm level (Hester and Baillie, 1998) so all the land of the farm within the ESA needs to enter as a whole (MAFF, 1998). Common land can only enter the ESA when all commoners agree on entry, and the Holne Moor Commons entered the scheme in 1998 (Goodfellow 1999, pers. comm.; Chapter 3).

Therefore, each livestock density could be expressed as numbers of animals observed at the catchment scale (61 ha), and were then divided by 15 to obtain an average density for the 15 periods of observation.

Table 8.2 shows the observed and expected frequencies and the χ^2-statistic per vegetation class. As a uniform distribution was hypothesised in the area, expected frequencies were obtained by using the total number of animals sighted, divided by the number of occasions. Each column in the table shows a separate analysis.

Results show that there is a substantial difference of sheep densities between the different vegetation classes. Cattle and ponies densities were shown to be largely insignificant, whereas for the sheep densities, a high significance level could be used with $p < 0.01$.

There is a relatively high number of sheep in the SG unit, and a relatively low density in both HG and the GG classes. Although the BG class shows a very close resemblance to the average grazing pattern, this area is still under higher pressure than the HG and GG classes. Again, it has to be kept in mind that this is a typical summer situation. In winter grasses die back and sheep turn to heath species (Havinden and Wilkinson, 1970; Hester and Baillie, 1998; Weaver *et al.*, 1998; Chapter 2), so the grazing behaviour becomes different.

If the relative areas of different vegetation units are taken into account, it is clear that sheep are abundant in a limited area of the catchment (SG only covers around 7%; Table 8.1). However, the bracken and grass unit (BG) also has a substantial stocking density of sheep, which increases the combined relative area to around 30% of the watershed area in total.

Table 8.2 shows no significant difference in cattle and pony frequencies between units, although there is a tendency to higher cattle grazing in the heather-grass mosaic. This confirms the fact that cattle and sheep never graze together, as their diet is different (Havinden and Wilkinson, 1970).

Livestock numbers observed in the catchment were converted to Livestock Units (LUs; MAFF, 1994; Chapter 3). As no information about the age of cattle was available for this study, an (arbitrary) average of 0.9 LU for cattle was used. Maximum grazing densities for land entered into the Dartmoor ESA scheme (Section 3.8) is repeated in Table 8.3.

Table 8.2: Chi square analysis of animal densities within the different vegetation classes.

Vegetation class			Livestock densities					
			Sheep (61 ha^{-1})	Sheep (ha^{-1})	Cattle (61 ha^{-1})	Cattle (ha^{-1})	Ponies (61 ha^{-1})	Ponies (ha^{-1})
SG	Short grass	Observed	75.51	1.24	8.05	0.13	1.01	0.02
		Expected	37.41		8.49		1.87	
		χ^2	38.81		0.02		0.40	
BG	Bracken and grass	Observed	33.51	0.55	7.84	0.13	1.89	0.03
		Expected	37.41		8.49		1.87	
		χ^2	0.41		0.05		0.00	
GG	Gorse and grass	Observed	24.58	0.40	8.06	0.13	1.79	0.03
		Expected	37.41		8.49		1.87	
		χ^2	4.40		0.02		0.00	
HG	Heather/grass mosaic	Observed	16.04	0.26	10.02	0.16	2.81	0.05
		Expected	37.41		8.49		1.87	
		χ^2	12.21		0.28		0.46	
Weighted mean			**28.73**		**8.33**		**1.93**	
χ^2			**55.83**		0.37		0.87	

O_i = observed, E_i = expected, χ^2_i= Chi square test statistic, p = 0.01 significance level: χ^2= 11.34.

Table 8.3: Maximum grazing requirements for land entered into the ESA scheme.

Stocking		**Moorland (Tier 1E)**	**Moorland (Tier 2B)**
General description		Do not graze so as to cause poaching, overgrazing or undergrazing.	Do not graze so as to cause poaching, overgrazing or undergrazing.
Summer	Ponies	0.04 LU ha^{-1}	0.04 LU ha^{-1}
	Additional	0.225 LU ha^{-1}	0.17 LU ha^{-1}
Winter	Ponies	0.04 LU ha^{-1}	0.04 LU ha^{-1}
	Additional	0.17 LU ha^{-1}	no cattle; 0.08 LU ha^{-1}

Source: MAFF, 1998.

The livestock distribution data set was used to calculate average grazing densities over the recorded period, in order to compare to the Dartmoor ESA requirements (MAFF, 1998). Although the scheme currently applied to the study area is Tier 1E, the second tier

(2B) was included to provide comparison to other moorland areas on Dartmoor. The number of LUs per vegetation unit was calculated, divided by the number of occasions (15) and divided by the total area (ha) covered by the vegetation class. Table 8.4 shows the resulting stocking densities, including the conversion to livestock units.

Table 8.4: Average estimated grazing densities within the study area.

vegetation class	sheep (ha^{-1})	cattle (ha^{-1})	ponies (ha^{-1})	sheep ($LU\ ha^{-1}$)	cattle ($LU\ ha^{-1}$)	ponies* ($LU\ ha^{-1}$)	total* ($LU\ ha^{-1}$)	total without ponies* ($LU\ ha^{-1}$)
SG	1.24	0.13	0.02	0.186	0.119	0.016	**0.321**	**0.304**
BG	0.55	0.13	0.03	0.082	0.116	0.031	0.229	0.198
GG	0.40	0.13	0.03	0.060	0.119	0.029	0.209	0.179
HG	0.26	0.16	0.05	0.039	0.148	**0.046**	0.233	0.187
weighted average	0.47	0.14	0.03	0.071	0.123	0.032	0.225	0.193

* *Values in bold indicate grazing densities higher than the maximum required by MAFF (1998) for ESA Tier 1E*

From Table 8.3 and 8.4 it is evident that average stocking rates are below (Tier 1E) or only just above (Tier 2B) the Dartmoor ESA requirements for summer conditions. However, when studying the vegetation classes separately, it can be deduced that in the SG class, the LU density is above the limit of both the ESA tiers. When the Tier 2B limits are taken into account, all vegetation classes exceed the stocking rates. From this it can be concluded, that the SG class can certainly be regarded as 'heavily grazed', with a tendency of BG towards heavy grazing.

If the observed pony densities are a representative estimate, the heather class (HG) is being overgrazed. Densities are close to the maximum in all other vegetation classes. It has to be realised, that when ponies graze in the area, maximum densities are reached at an earlier stage. For example, the limit of 0.04 LU ha^{-1} is equal to 1 pony 25 ha^{-1}. However, ponies were only observed on three out of 15 occasions, and a more extensive survey should be carried out to validate the findings as presented here.

It has to be concluded, that the Dartmoor ESA requirements are a rough figure, especially when applied to a large area such as the Holne Moor Commons. Although adjusted after initial guidelines set for all open hill areas in Britain (Hester and Baillie, 1998), these requirements still do not represent the different vegetation communities on the Dartmoor Commons (MAFF, 1997). As shown above, it is very unlikely that livestock is distributed homogeneously over the area, so heavy grazing could occur even when average levels are not above the limit. This heterogeneous grazing behaviour, which has also been reported by other researchers on other British heather moorlands (*e.g.* Clarke *et al.*, 1995; Hester and Baillie, 1998), has to be taken into account to facilitate a better estimate of grazing densities.

The Heather Utilisation Survey is carried out by the Dartmoor National Park Authority every year and estimates the grazing pressures on heather. This survey showed a slight improvement between 1998 and 1999 (DNPA, 2000, unpublished data) after the introduction of the ESA-scheme. Although these results are at the Commons scale, they are comparable with results presented here. According to the survey, the main heather area in the south (HG and GG) showed relatively little signs of grazing and was classified as 'not overgrazed nor chronically heavily grazed'. The area in the valley floor, mainly taken up by the SG and BG classes, is classified as 'no heather (other vegetation communities)', as no heather is present (DNPA, 2000, unpublished data).

The vegetation coverage observations of the hillslope TDR-grid were reclassed into the air photo vegetation groups. If it was assumed that the air photo vegetation groups represented the different grazing pressures in the area, plant species could be compared to grazing intensity within the TDR grid. It was shown that *Agrostis capillaris*, *Galium saxatile*, *Pteridium aquilinum* and *Sphagnum* were observed significantly more with higher stocking densities. *Festuca ovina*, *Calluna vulgaris*, *Erica tetralix* and *Erica cinerea* were significantly less abundant. Although the use of the vegetation classes as representation of grazing is debatable at the point scale, vegetation compositions are comparable to results presented elsewhere (*e.g.* Nolan *et al.*, 1995; Hester and Baillie, 1998; Weaver *et al.*, 1998; Chapter 2).

8.2.4 Spatial stocking distributions within vegetation classes

Livestock are not grazing the catchment homogeneously. Livestock distributions within certain vegetation classes are not equally distributed either, as can be seen from Fig. 8.3. Livestock tend to graze in the vicinity of more heavier stocked vegetation types, *e.g.* the SG class, mainly in the case of sheep stocking. This behaviour of sheep grazing was also observed by Hester and Baillie (1998) and Clarke *et al.* (1995) on heather moorlands in Scotland. This indicates, that in a heather stand, grazing densities are greater when this stand is close to a more palatable vegetation community. In the study area, this means that within certain vegetation types (other than SG) with an average stocking rate close to the ESA limit, it is likely that rates will exceed the stocking limit if this vegetation type occurs in the vicinity of SG. Therefore, one would expect a higher stocking density on locations closer to SG (and BG) classes than further away.

If there were no influence in the vicinity of other vegetation types on the livestock distribution, it would be expected that grazing densities (F_x) were uniformly distributed over all distances. However, distance classes do not cover equal areas within the catchment. For example, a distance of 10 m to the SG group occurs much more often than a distance of 100 m to the same group. Therefore, F_x is divided by the percentage area (A_x) the distance class occupies within the study area. This was analysed by using a stocking index (Equation 8.1):

$$SI_x = \frac{F_x}{A_x} \quad [8.1]$$

where:

SI_x = Stocking index for vegetation type x;

F_x = Number of animals in distance class to vegetation type x;

A_x = fraction area of distance class to vegetation type x.

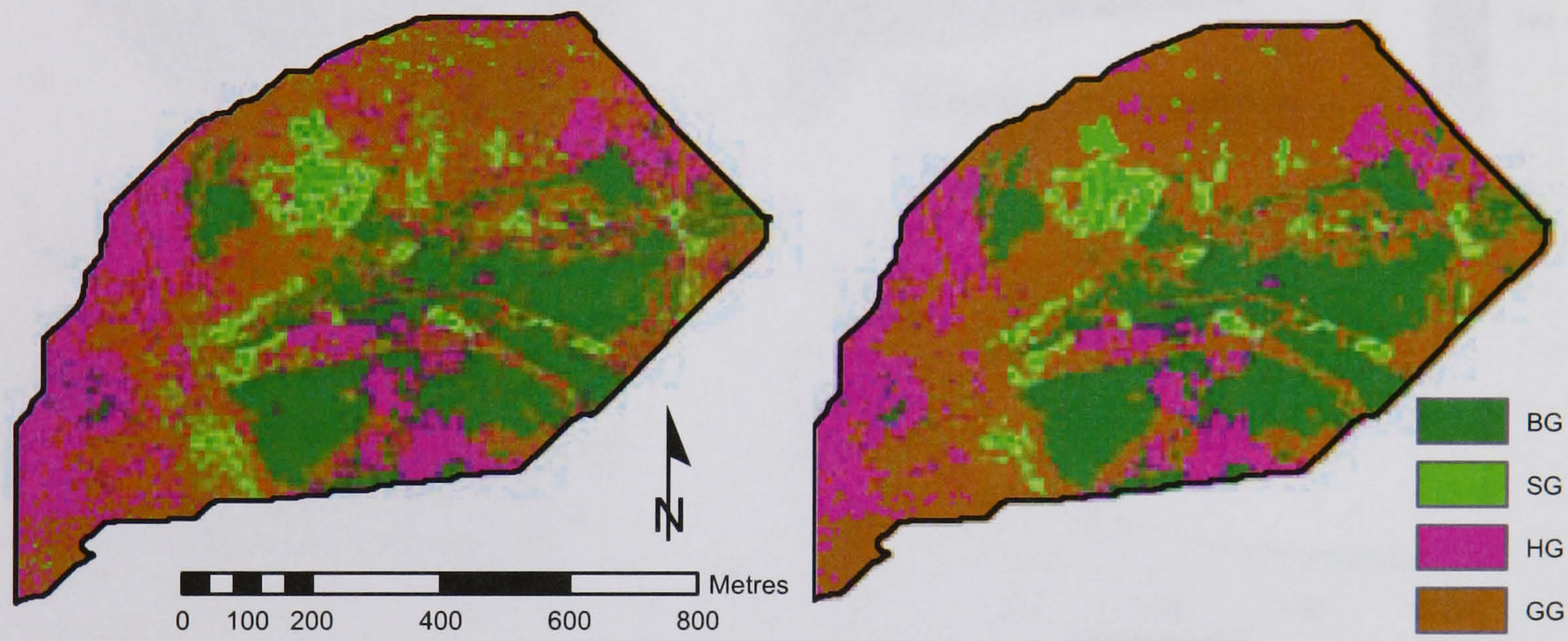


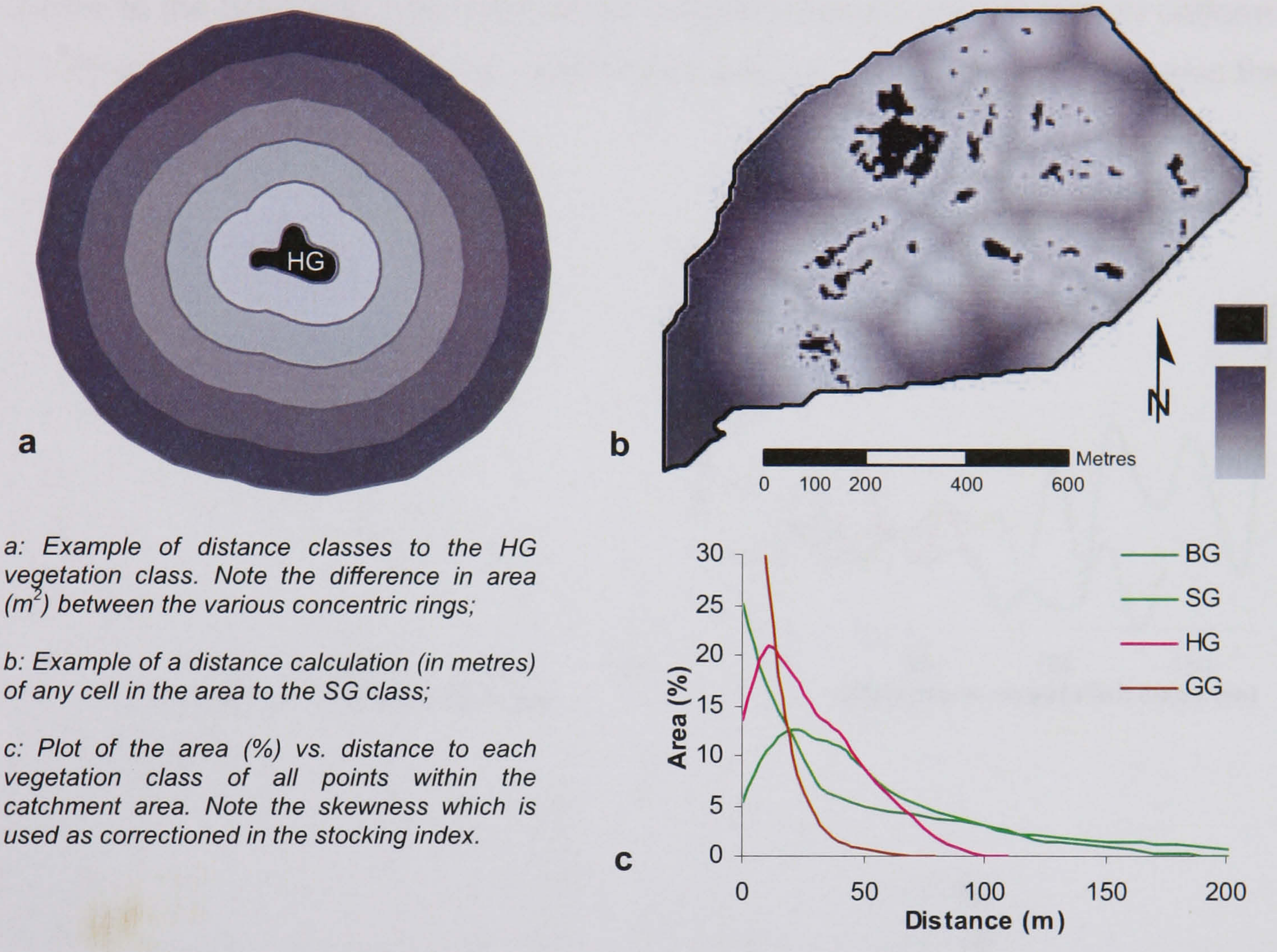
Figure 8.4: Removal of single isolated cells using a 3-cell radius (5.5 m) circular moving window in a GIS. The figure shows the original data (left) and the enhanced image (right).

If grazing densities are evenly distributed within vegetation groups, the stocking index *vs.* distance should be constant. If livestock has a preference for a certain vegetation type, the index is expected to be higher closer to that particular vegetation type.

In order to calculate the stocking index, first the air photo image (cell resolution 1.77 m) was simplified to remove the noise (single, isolated cells). This was done using a filter operation in a GIS (Figure 8.4; Chapter 4).

With the enhanced image, the distance from each cell (resolution 1.77 m) to the cells of all different vegetation types was calculated. Distances were categorised into distance classes (A_x) using a 10 m interval. Fig. 8.5a shows an example of the different distance classes. Fig 8.5b shows the distance from each cell to the SG class. As expected, these calculations yielded a heavily skewed histogram with the area to the distance from every cell in the catchment (Fig. 8.5c). Having established the locations of the distance classes, the sum of individual livestock units per distance class (F_x) could also be established in a GIS.

Figure 8.6 shows the results of the analysis. Although strictly speaking, interpolation lines between samples are not allowed because of the ordinal data, this was used in this figure for interpretation purposes following Hester and Baillie (1998).



a: Example of distance classes to the HG vegetation class. Note the difference in area (m^2) between the various concentric rings;

b: Example of a distance calculation (in metres) of any cell in the area to the SG class;

c: Plot of the area (%) vs. distance to each vegetation class of all points within the catchment area. Note the skewness which is used as correctioned in the stocking index.

Figure 8.5: Distance calculations of the four vegetation classes.

The distribution of sheep shows, as expected, a relatively high stocking index in the vicinity of the SG-class with a decreasing trend towards the maximum distance possible within the catchment (170 metres). This was also found within the BG-class, but with a shorter maximum distance of 140 metres. Similar results were obtained by Welch (1984), Clarke *et al.* (1995) and Hester and Baillie (1998) on Scottish heather moorlands, with a decrease in heather utilisation with distance to grass. Hester and Baillie (1998) showed that further than 3 to 5 metres away from grass in heather, grazing was virtually absent. In the study area, the largest decline was in the first 25 metres. The interpolation line of the HG class shows that grazing generally increases further away from heather, which also corresponds with the results from Welch (1984), Clarke *et al.* (1995) and Hester and Baillie (1998). The GG vegetation class shows a more homogeneous distribution, until the maximum distance is reached at 50 metres.

This indicates that in summer, sheep tend to graze in the vicinity of SG and BG, and further away from HG. The presence of GG does not appear to have an effect on grazing behaviour. Combined with the fact that most sheep were observed within the SG and BG classes, these vegetation types show relatively high grazing pressures.
For cattle, the opposite is found, in that densities are generally positively correlated with distance to the SG class. Although the distance distributions are not entirely uniform in the other three vegetation classes, no clear trend could be found here. This was also the case for ponies.

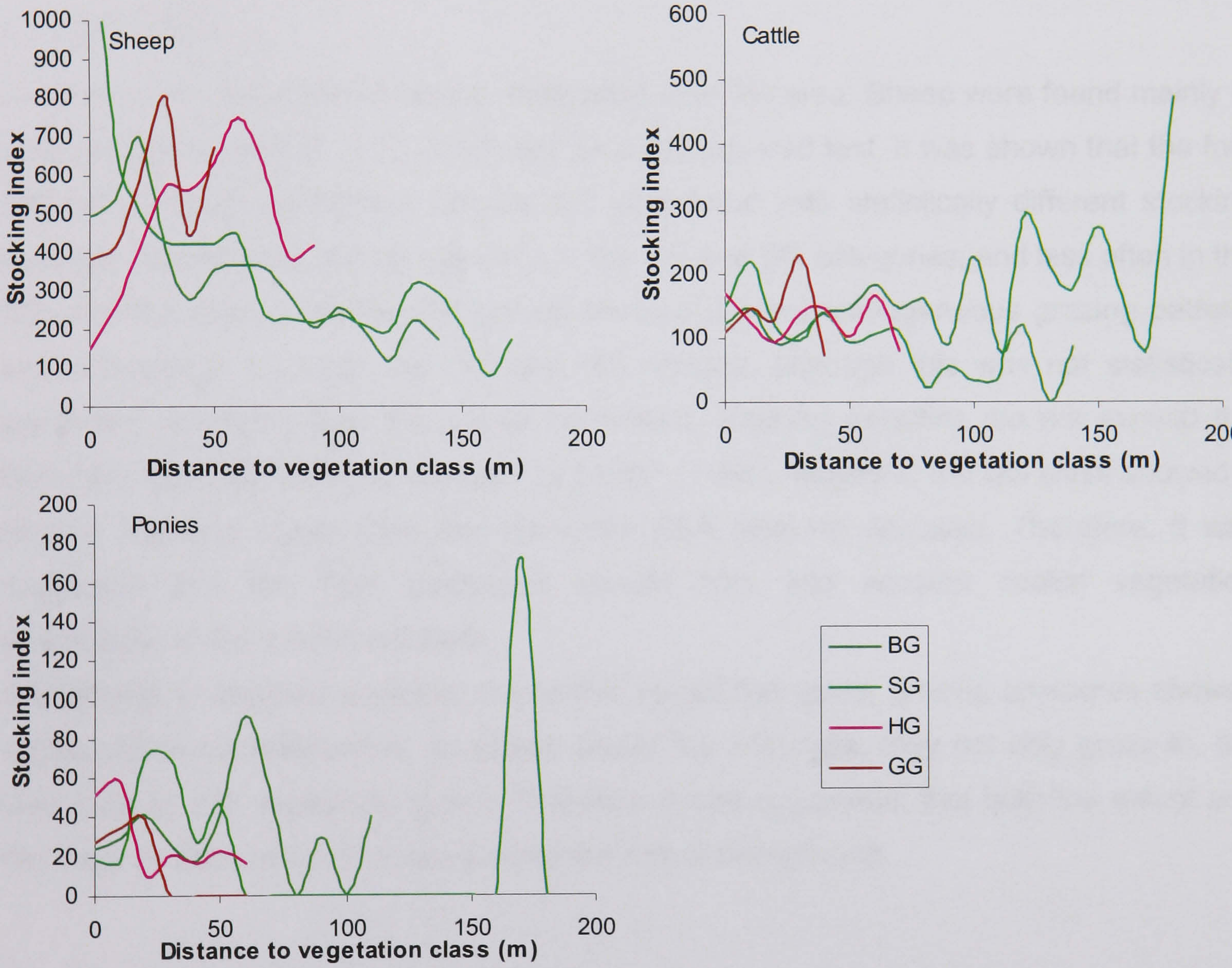


Figure 8.6: Stocking index vs. distance to vegetation class.

It can therefore be concluded, that when studying grazing pressure, not only the different proportions of vegetation should be taken into account, but also the fragmentation of the different vegetation communities should be regarded. Fragmentation will cause a relatively long border between heather and grass, increasing the pressure on heather. In other words, if the vegetation pattern becomes more fragmented (*e.g.* a heterogeneous pattern of heather and grass patches), with increased grazing on grass, grazing within the heather stands will increase. These findings correspond with the results by Clarke *et al.* (1995) and Hester and Baillie (1998).

Therefore, large areas of more homogeneous heather stands would reduce the risk of overgrazing within heather stands. In the study area, it has been shown that the highest grazing pressures in heather appear in the first 25 m from grassy areas. Although this is a greater distance than found by Hester and Baillie (1998), this distance could be used as a guideline to prevent fragmentation in the study area.

8.2.5 Summary

Livestock were not homogeneously distributed over the area. Sheep were found mainly in three distinct areas (Fig. 8.2), confirmed by a Chi squared test. It was shown that the four different air photo vegetation classes are associated with statistically different stocking densities. Sheep were mostly observed in the SG and BG categories, and less often in the GG and HG classes. Cattle and ponies showed a more homogeneous grazing pattern, with a tendency to prefer the GG and HG classes, although this was not statistically significant. Averaged over the whole catchment, stocking densities did not exceed the Dartmoor ESA requirements adopted by MAFF (1998). However, the SG class showed a grazing pressure higher than the maximum ESA stocking densities. Therefore, it was suggested that the ESA guidelines should take into account spatial vegetation distributions at the catchment scale.

Additionally, it was demonstrated that within vegetation types, grazing pressures showed a heterogeneous distribution. As sheep prefer the SG class, they not only graze in, but also close to this vegetation group. Therefore it was suggested, that both the extent and the fragmentation of heather determines the risk of overgrazing.

8.3 The impact of burning at the plot scale

Although burning heather has a direct effect on the vegetation, the impact on the vegetation-soil-hydrology system is much more complex. This section will focus on the direct effects of the burn on soil temperature and reduced biomass. The short and possible longer term effects of burning on the soil moisture will also be outlined. The experimental burn will be compared to a farmer's burn in order to assess the comparability of the experiment to the traditional swaling. The results of the water repellency tests of the topsoil and the overland flow experiments are also described.

8.3.1 Fuel load

On the basis of visual comparison to the farmer's burns, the experimental burns were equivalent in terms of velocity and intensity. One important conclusions of all prescribed fires observed on Dartmoor, is that they are signified by a short, shallow burn, and are therefore very different from the more intensive wildfires. These fires have been observed burning into the peat, as for example occurred during a fire in April 1997 at Trendlebere Down.

Vegetation on the burn plots was *Calluna* mainly. Above ground living biomass of the control plots were established to be around 900 g m^{-2} (9000 kg ha^{-1}) dry matter (Section 4.8.1), ranging from 680 to 1230 g m^{-2}. This is typical for heather in the building phase (around 10,000 kg ha^{-1}; Gimingham, 1975). The heather cover of the plots was probably not ideal for a burn, but these conditions were the best possible within the catchment area due to the decline of heather (DNPA, 2000, unpublished data; Section 8.2.3). In both burned plots, the vegetation dry matter which remained was 400 g m^{-2} on average, so the net fuel load burned was in the range of 500 g m^{-2}, between 160 and 640 g m^{-2}. This excluded the extra *Molinia* and bracken added in places to keep the burn going. Most of the fuel load consisted of thin branches and leaves of the heather and *Molinia*, leaving the thicker stems. These data show the heterogeneous nature of the fuel load at the plot scale. This is reflected in the intensity of the burn and the effected soil properties.

8.3.2 Temperature profile

Soil temperatures before, during and after the burn showed a very heterogeneous and irregular pattern. Temperatures at the soil surface reached maximum values ranging from 80 to 410 °C (Fig. 8.10).

At 1 cm depth, the highest temperature reached was around 70 °C, whereas in other locations the temperature at this depth hardly increased. At 3 cm depth, one of the thermistors recorded an increase of only 5 °C, the other did not show any increase. The period of increased temperature was relatively short, between 5 and 8 minutes. The temperature in moist soils did not exceed 100 °C, which only occurs when the water has evaporated (Aston and Gill, 1976; DeBano *et al.*, 1976).

Similar soil surface temperatures were found with maximum temperatures between 50 and 430 °C in a heathland soil in Brittanny, France (Forgeard and Frenott, 1996) between 300 and 500 °C (Whittaker, 1961). Both Whittaker's (1961) measurements were carried out in heather stands between 10 and 35 years old, but did not indicate the stand height of the vegetation. Mallik *et al.* (1984) reported maximum soil surface temperatures of up to 755 °C (canopy 767 °C) in heather in the late building phase (15-20 years; Gimingham, 1975). Gimingham (1972) also suggested that canopy temperatures should not exceed 400 °C in order for the heather to regenerate rapidly.

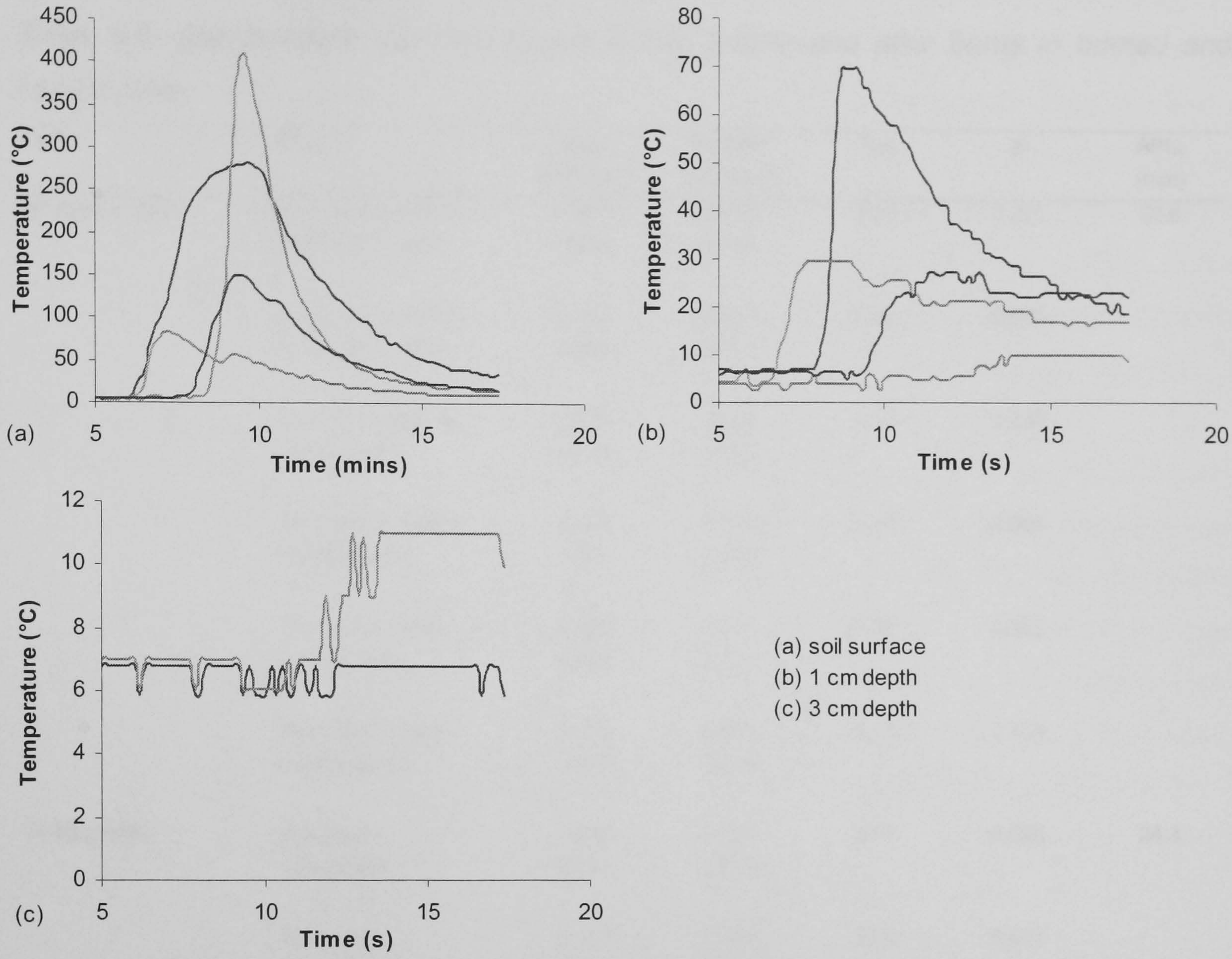


Figure 8.7: Soil temperature vs. time.

It can therefore be concluded that the experimental burn is representative in terms of time and intensity and in general did not exceed the maximum temperature for a prescribed heath burn. Also the shallow effect of the burn in the soil is representative for a heather burn. This has important consequences for soil properties directly affected by temperature, like water repellency, organic matter and soil moisture content. These properties will only be affected in the uppermost topsoil.

8.3.3 Fire and the effect on soil moisture

Soil moisture of the top 6 cm was measured on five occasions: twice on the day of the burn (before and immediately after the burn), and on three occasions within a subsequent 5-month period. Recordings were taken with a thetaprobe on a regular grid within the 3 x

3-metre plot, totalling 36 samples per plot (Section 4.8.1). Results are presented in Table 8.5 and Fig. 8.8.

Table 8.5: Soil moisture contents (upper 6 cm) before and after burns in burned and control plots.

Date	Plot	θ_{mean} ($cm^3\ cm^{-3}$)	st. dev. ($cm^3\ cm^{-3}$)	T_{KW}	p	API_{18} (mm)
15 March 1999	Burn plot I, before	0.571	0.012	1.10	0.295	26.6
	Burn plot I, after	0.568	0.015			
	Burn plot II, before	0.561	0.020	8.82	0.003	
	Burn plot II, after	0.574	0.012			
	Burn plot I, before	0.571	0.012	4.73	0.030	
	Control plot I	0.564	0.016			
	Burn plot II, before	0.561	0.020	11.47	0.001	
	Control plot II	0.573	0.016			
	Burn plot I, after	0.568	0.015	1.16	0.282	
	Control plot I	0.564	0.016			
	Burn plot II, after	0.574	0.012	0.11	0.735	
	Control plot II	0.573	0.016			
14 May 1999	Burn plot I	0.581	0.007	5.01	0.025	24.3
	Control plot I	0.575	0.010			
	Burn plot II	0.578	0.009	5.14	0.023	
	Control plot II	0.583	0.008			
22 June 1999	Burn plot I	0.530	0.034	15.28	0.000	10.2
	Control plot I	0.472	0.067			
	Burn plot II	0.520	0.042	9.91	0.002	
	Control plot II	0.487	0.049			
31 July 1999	Burn plot I	0.396	0.071	20.40	0.000	4.4
	Control plot I	0.311	0.061			
	Burn plot II	0.368	0.080	15.72	0.000	
	Control plot II	0.296	0.046			

Values in grey denote a non-significant difference ($p < 0.05$)

Soil moisture values of the topsoil before and after the burn were very similar. In plot I, soil moisture values decreased slightly, but not significantly. Yet in plot II, the soil moisture content had increased during the burn, which was tested significant statistically using a Kruskal-Wallis test. However, this significant difference was an artefact because of the relatively low standard deviation, which was lower than the error margin of the thetaprobe measurement (0.02 $cm^3\ cm^{-3}$; Delta-T devices, 1996). It was also evident, that the control plot differed significantly with the same margin of their burned plots, with lower values in plot I and higher in plot II. As a conclusion, soil moisture values did not change significantly over the top 6 cm over the course of the burn. Forgeard and Frenot (1996) (Section 2.8) recorded similar results on Brittany heathlands, with no significant decrease in soil moisture over the top 5 cm either at 150 or 300 °C. However, they did find a decrease in soil moisture content over the top 2.5 cm with the 300 °C treatment only, with an increase at 2.5 to 5 cm depth. They attributed this to downward movement of soil water from the top 2.5 cm, but did not give an explanation for the downward flux. If this phenomenon also occurred in the study area, combined with the shallow temperature impact of the fire and the relatively large sample depth, it could explain the lack of decrease in soil moisture measured.

On a relatively wet day two months after the burn (14th of May 1999), soil moisture was measured. Antecedent wetness was similar to the conditions on the date of the burn, with an API_{18} of 24.3 mm. The mean soil moisture levels of all plots, both burned and control were similar, as were the standard deviations (± 0.006 cm^3 cm^{-3}). However, on drier occasions (22nd of June and 31st of July, with an API_{18} of 10.2 and 4.4 mm, respectively; Table 8.5), mean soil moisture under the burned plots was significantly higher than under the control plots. In this case, the difference was much larger (0.046 and 0.079 cm^3 cm^{-3}, respectively, Fig. 8.8) and was well above the standard error of the thetaprobe (Delta-T devices, 1996). The difference could therefore be regarded as truly significant.

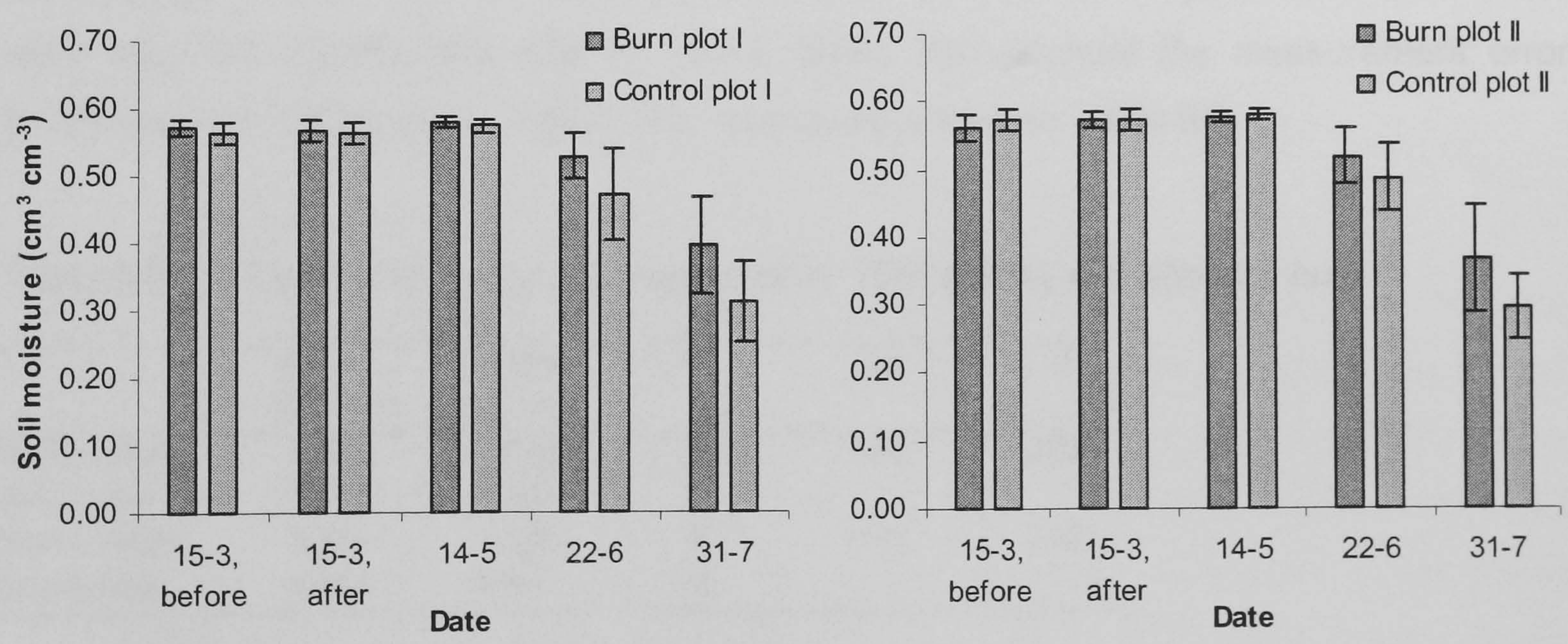


Figure 8.8: Average soil moisture values with standard deviations in the burned and unburned plots.

These findings are in line with results by Mallik *et al.* (1984) in Northeast Scotland, who showed that soil retains more water at 0-6 cm depth under burned conditions when pF> 1. This might be due to the blocking of larger (transmission) pores by the inwashed ash after the burn. Therefore, the moment of sampling in relation to the first rainfall after the burn is crucial to the estimation of the effect of burning on soil moisture levels (Ternan, 1999, pers. comm.). No soil water retention curves measurements were carried out on the burn and control plots to establish the different pore distributions, unfortunately.

In the study area, the transpiration by the vegetation might also play a role in the significantly higher soil moisture contents under burned conditions. The intact vegetation cover on the control plots transpires more water, therefore depleting the soil moisture at a faster rate in drier conditions. Indeed it has been shown in Chapter 7, that in dry conditions, local vegetation is an important factor in determining soil moisture content. However, it could be expected, that soil moisture levels would be significantly drier when the soil is not protected by vegetation, due to increased evaporation rates directly from the soil. This might be the case for a shallow layer at the ground surface, in the order of less than a centimetre, in a relatively wet area such as Dartmoor. Unfortunately, measurements of this shallow depletion of soil moisture were not carried out in this study.

The standard deviations of the thetaprobe measurements are higher in drier situations, increasing the heterogeneity of moisture in the soil. Similar observations in unburned conditions have been made in the TDR grid and are described in Section 6.4.

TDR was used to measure soil moisture over the top 20 cm in the burned and control plots (Chapter 4), before and directly after the burns. Over this depth, moisture contents were also not significantly different when taking into account the measurement error (0.035 $cm^3\ cm^{-3}$; Roth *et al.*, 1992). The results are shown in Table 8.6.

Table 8.6: Soil moisture values as measured by TDR before and after the burn

	θ_{mean} ($cm^3\ cm^{-3}$)	st dev ($cm^3\ cm^{-3}$)	n	T_{KW}	p
Burn I, before	0.52.2	0.0384	9	4.50	0.034
Burn I, after	0.55.4	0.0229	8		
Burn II, before	0.50.6	0.0256	9	0.16	0.690
Burn II, after	0.49.5	0.0491	9		

8.3.4 Representativity of the burning experiment

To compare findings with a fire as carried out by farmers directly after a burn, soil moisture measurements were carried out two hours after a prescribed burn on the eastern side of Venford reservoir (Section 4.8.3). No significant difference was found in soil moisture between burned and unburned conditions (Table 8.7). Therefore, soil moisture conditions of the experimental burn were comparable to those from the farmer's in the short term directly before and after the burn.

Table 8.7: Statistics of the farmer's burn.

Experiment		θ_{mean}	st. dev.	n	T_{KW}	p
Cross	Burned	0.565	0.026	13	0.35	0.552
	Unburned	0.568	0.015	42		
Transect	Burned	0.575	0.011	17	0.04	0.836
	Unburned	0.577	0.009	17		
Cross + Transect	Burned	0.571	0.019	30	0.87	0.350
	Unburned	0.570	0.014	59		

8.3.5 Water repellency

Often, water repellency has been recorded after a vegetation burn (*e. g.* De Bano *et al.*, 1976; Doerr *et al.*, 1996). This effect causes a barrier for water to infiltrate (Dekker, 1998; Ritsema, 1998). Initially, water repellency was to be tested with the water drop penetration test (WDPT; Section 4.8; Ritsema, 1994; Doerr, 1998) on 36 points within each plot. Directly after the burning experiment, water repellency was tested first on several randomly chosen locations within the plot, both on bare ground patches as well as on ash-covered soil. No evidence of water repellency was found, and therefore the test was not continued. It was concluded that water repellency did not occur within the study area, because of high soil moisture values and short, low intensity burns.

8.3.6 Overland flow after an experimental burn

In order to test whether there was an increase in overland flow after a burn in the study area, a rainfall simulation experiment was set up on both burned plots and one control plot (Section 4.8.2). Burned plot I received 44 mm in 60 minutes, ranging from 25 to 80 mm (Fig. 8.9). Burned plot II received 40 mm, but showed a much more homogeneous rainfall distribution over the plot, with a minimum of 33 and a maximum of 43 mm hr^{-1}. The control plot showed the lowest rainfall of the three simulations, between 20 and 36 mm, averaging at 30 mm hr^{-1}.

The difference in amount and distribution was attributed to the pump used and some (minimal) wind effects. Also the nozzle used, which was the smallest available, caused some irregularities, as it was tried to keep the amount as small as possible to represent a typical Dartmoor intensity. Typical maximum average storm rainfall intensities in the area were around 9 mm hr^{-1}. The largest rain event showed an amount of 45 mm in ten hours (Section 5.3.2). Therefore, it could be concluded that the rain intensity of the simulation could not be regarded as a typical Dartmoor rainstorm. However, with the equipment available, no more representative (*i.e.* lower and more homogeneous) rainfall could be simulated. Additionally, average rainstorms over 4 mm per event lasted over 5 hours in the study area, showing that a one-hour simulation is relatively short. Yet because of the resources and manpower used, it was impractical to increase the length of the simulations.

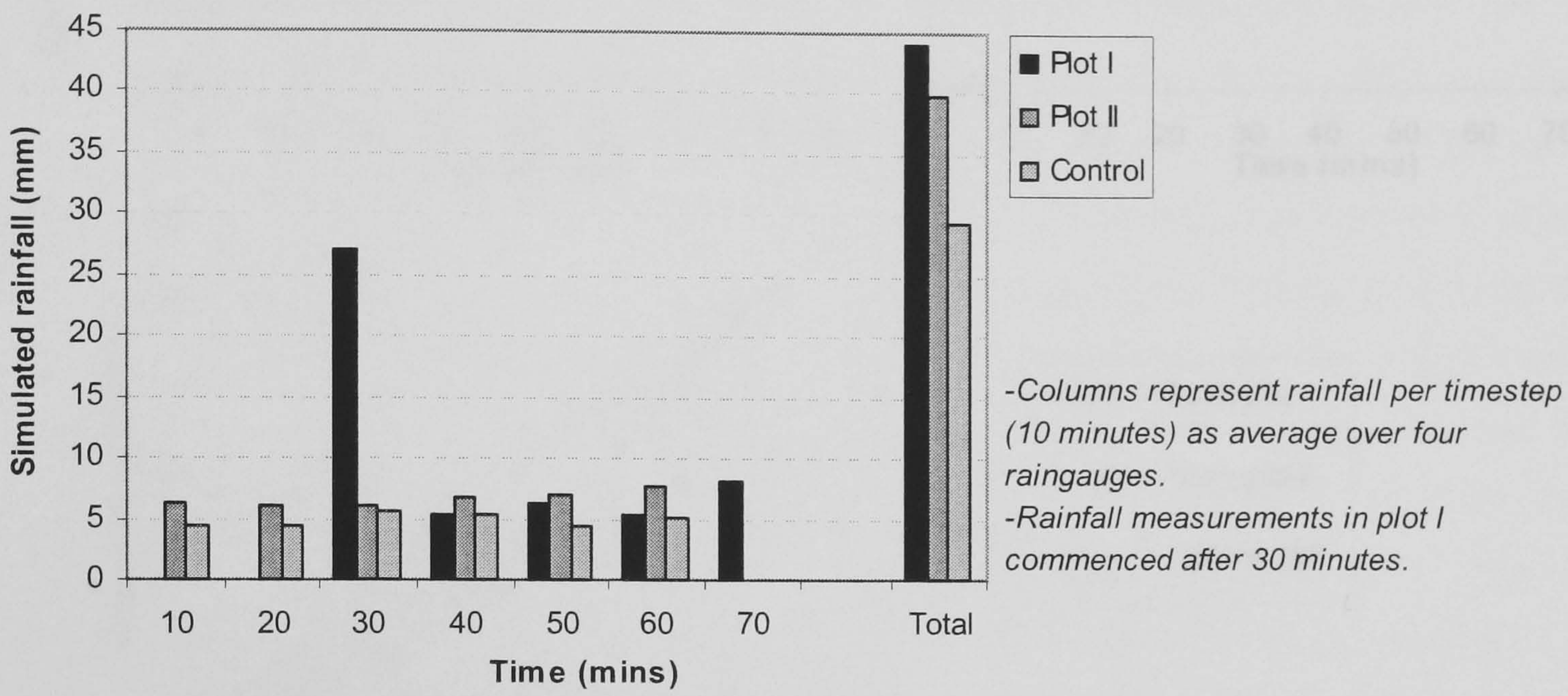


Figure 8.9: Simulated rainfall amounts per time step.

During the course of the three simulations, no overland flow was observed and all rainfall infiltrated into the soil. Soils wetted up evenly over time, with an average increase of 0.02 to 0.03 $cm^3 cm^{-3}$ in the top 6 cm (n = 8, Fig. 8.10). A decrease in standard deviation was also observed, indicating a transition towards a more homogeneous moisture distribution over time. This is in agreement with the findings within the hillslope and grazing TDR grids.

TDR measurements over the top 20 cm (n = 2) showed a much higher increase in soil moisture of between 0.05 and 0.10 $cm^3 cm^{-3}$. Also, the TDR measurements start with lower initial soil moisture contents than the thetaprobe measurements, but the final soil moisture contents are similar, close to the wetness threshold between the dry and wet preferred states (Chapter 6). This is due to the wetting front, wetting up the lower horizons through the course of the simulation. However, the difference in method could also be causing part of the difference in soil moisture content (Section 4.3). As can be observed from Fig. 8.10, the wetting up curve appears to reach an asymptotic value, which is close to 0.60 $cm^3 cm^{-3}$, the wetness threshold. The rainfall per time interval was linear, however. Although measurements were not carried out long enough to fully explore this curve, a possible reason for this levelling off may be the increased hydraulic conductivity, when transmission pores started to fill. The asymptotic value would then be reached when infiltration equalled hydraulic conductivity.

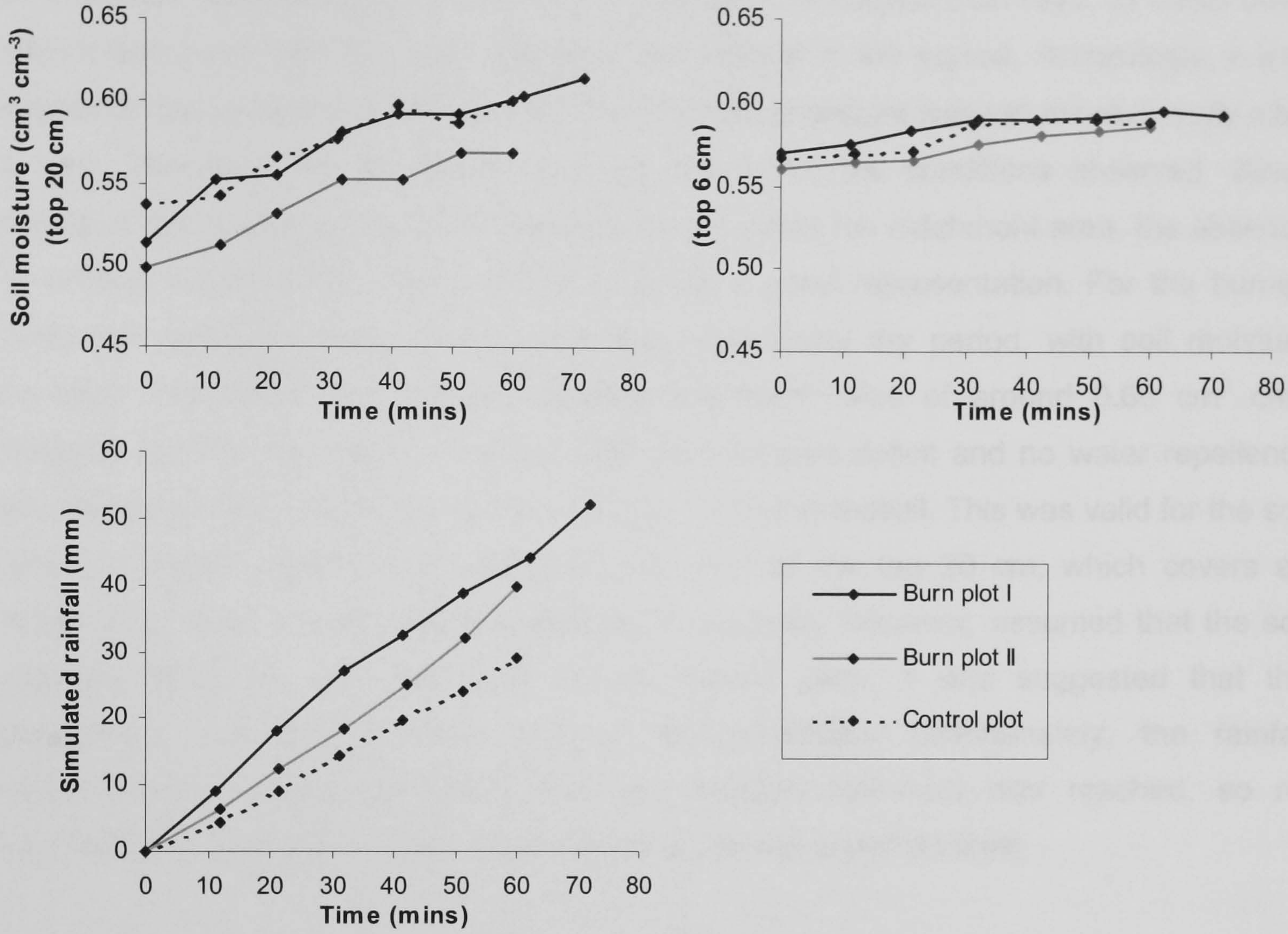


Figure 8.10: Soil moisture change and cumulative rainfall during simulation.

Table 8.8: Increase in soil moisture content during the rainfall simulation.

Plot	Total rainfall (mm)	Soil moisture thetaprobe (6 cm)			Soil moisture TDR (20 cm)		
		θ_{start}	θ_{finish}	x 10^{-3} cm^3 cm^{-3} mm^{-1}	θ_{start}	θ_{finish}	x 10^{-3} cm^3 cm^{-3} mm^{-1}
I	44.1	0.570	0.595	0.56	0.514	0.603	2.02
II	39.9	0.560	0.586	0.65	0.498	0.569	1.78
Control	29.3	0.567	0.589	0.73	0.537	0.600	2.14

No difference in soil moisture increase was observed between the burned and control plots. However, when the increase in soil moisture is expressed as increase per unit of rainfall (cm^3 cm^{-3} mm^{-1}; Table 8.8), the unburned topsoil appears to hold more water than the topsoil of the burned plots. Although the data is limited, this could indicate a decrease in water holding capacity due to the inwash of ash during the course of the simulation, which conflicts with the results of Mallik *et al.* (1984), but is similar to findings by Ternan and Neller (1999) shortly after the fire. However, no analyses on water retention under burned and unburned conditions were carried out in the study area.

Overland flow was not observed, neither in the burned plots nor in the control plot. This is an important observation in respect to the hillslope hydrological pathways, as it has been shown previously that the main pathways are located in the topsoil. Accordingly, it was expected that widespread overland flow was not an important issue in areas directly after a burn. However, this conclusion is only valid within the conditions observed. Since overland flow is only occasionally being observed within the catchment area, the absence of surface runoff in the control plot is probably a good representation. For the burned plots, the simulation was carried out during a relatively dry period, with soil moisture contents well below the average wetness threshold value of around 0.60 cm^3 cm^{-3} (Chapter 6). The soil had a relatively high soil moisture deficit and no water repellency was observed, so all water applied was stored within the topsoil. This was valid for the soil moisture range between 0.50 and 0.60 cm^3 cm^{-3} of the top 20 cm, which covers an reasonable range of soil moisture contents in the area. However, assumed that the soil moisture threshold was applicable to the burned plots, it was suggested that the experiment was only representative in dry conditions. Unfortunately, the rainfall simulations were stopped before the soil moisture threshold was reached, so no information is available on the soil conditions in the wet preferred state.

8.4 The causal-relationship diagrams

Vegetation distribution is a function of soil, (micro) climate and hydrology, but conversely, the vegetation also affects the soil and the hydrology (Gimingham, 1975; White, 1997; Van Breemen and Finzi, 1998). Obviously, land management also affects these variables (Droogers, 1997; Fitzjohn *et al.*, 1998; Pulleman, 2000; Chapter 2). Therefore, extracting possible impacts of land management on the soil and hydrology, either directly or via a change in vegetation can be complex and are central to this thesis. In order to get an overview of the different interactions observed in the study area, several causal-relationship diagrams have been created, using the results of this study. The diagrams (Figs. 8.11 to 8.13), depict the significant correlations between the different soil, topographic and vegetation variables in order to visualise the complex interactions. They can be used as a guideline in the following sections to study the possible effects of land management on the soil and hydrology. In Section 8.7, the different diagrams will be compiled into one figure to form a conceptual model of the dynamics relationships of the moorland system within the study catchment.

The diagrams are a reflection of the catchment moorland system (Chapter 2), which could be regarded as a dynamic equilibrium: If one of the factors from the system is changed, this will have an impact on a combination of other components, shifting the system into a new state of balance.

In the diagrams, continuous lines indicate a statistically significant positive correlation, whereas dotted links signify a significant negative correlation. A significance level of $p<0.10$ was used here, to be able to describe the subtleness of the relationships. In order to keep the diagrams as simple as possible, correlation coefficients were not indicated, nor were the different levels of significance. These data can be found in earlier chapters.

The relationships within the diagrams are strictly statistical, and do not necessarily depict a two-way influence. For example, it has been shown that local slope angle has a negative correlation with soil moisture. This could indicate, that in areas with an increased gradient, soil moisture levels are generally lower. Obviously, it does not mean that if at a certain location the soil moisture level increases, the slope angle decreases. Therefore, some relationships have a one-way nature, whereas in other cases, components can both affect the other.

In some cases correlations were only significant for certain soil depths. Relationships have only been indicated when two or more correlations were significant out of the four depths. Hence, the diagrams have to be regarded as a simplified visualisation of the complex nature of the different relationships. The subtleties are, where necessary, discussed further in the text.

Fig 8.11 shows the causal relationships between soil properties on the local scale based on the results of this study and focuses on the influence of soil moisture. The figure acts as a summary of the findings of Chapter 6, and shows the difference between the 'wet' and 'dry' preferred states. As in the 'wet' preferred state, the topographic controls are becoming more important, the influence of topography on soil moisture content is depicted in Fig. 8.12. Although the correlations in this figure are similar in both 'wet' and 'dry' preferred states, the relationship between soil moisture, the topographic index and slope angle are more significant in the wet state.

Fig. 8.13 shows the complex nature of the relationships between single vegetation species and soil properties. The correlations between soil properties and soil moisture are described in Fig. 8.11, and are therefore omitted from this figure. In the following sections, the impacts of land management on soil properties will be analysed, in order to fit this component into the figures above.

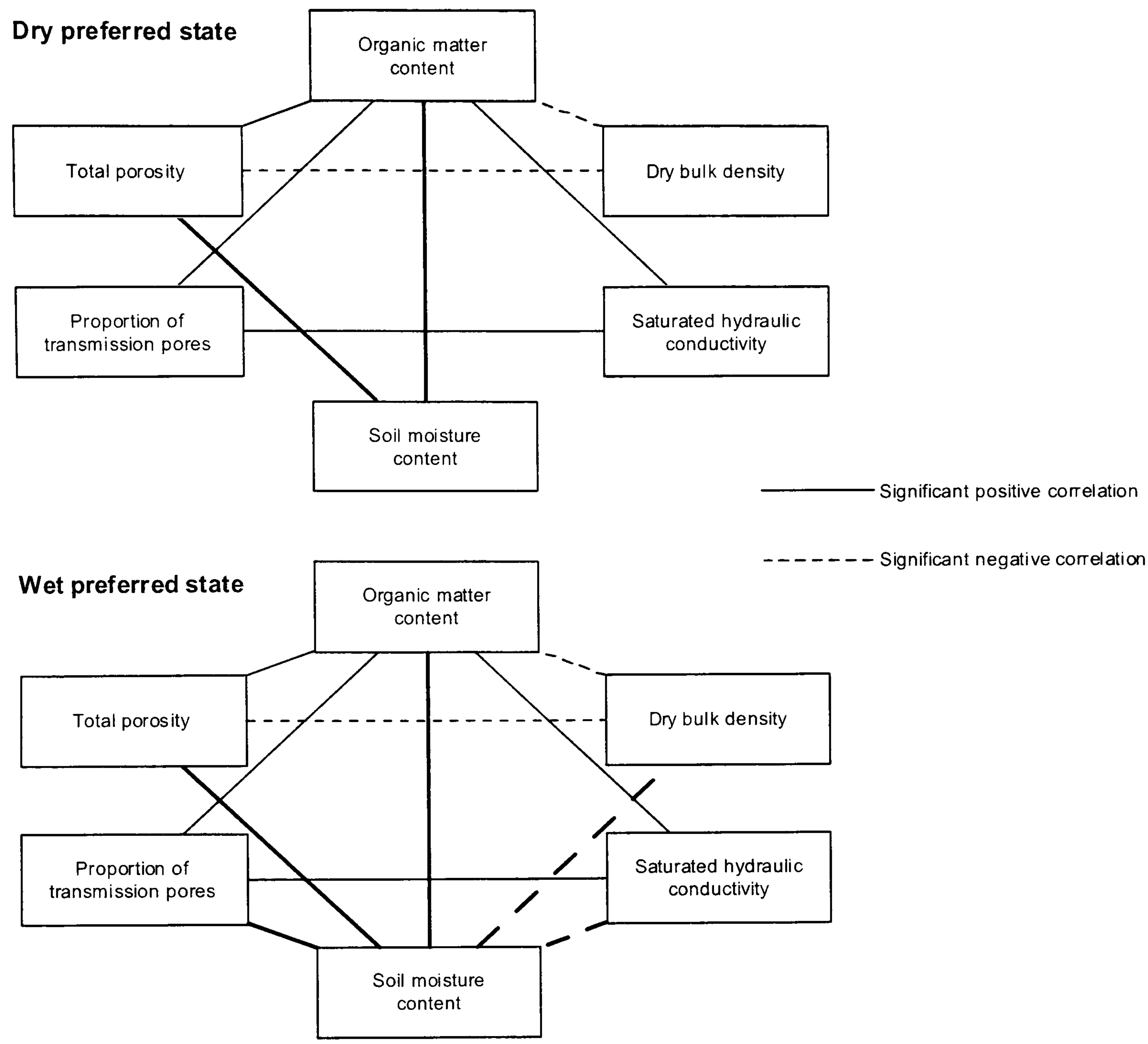


Figure 8.11: Causal-relationship diagram between soil properties. The bold lines indicate the correlations with soil moisture content, which depend significantly on the 'dry' and 'wet' preferred states.

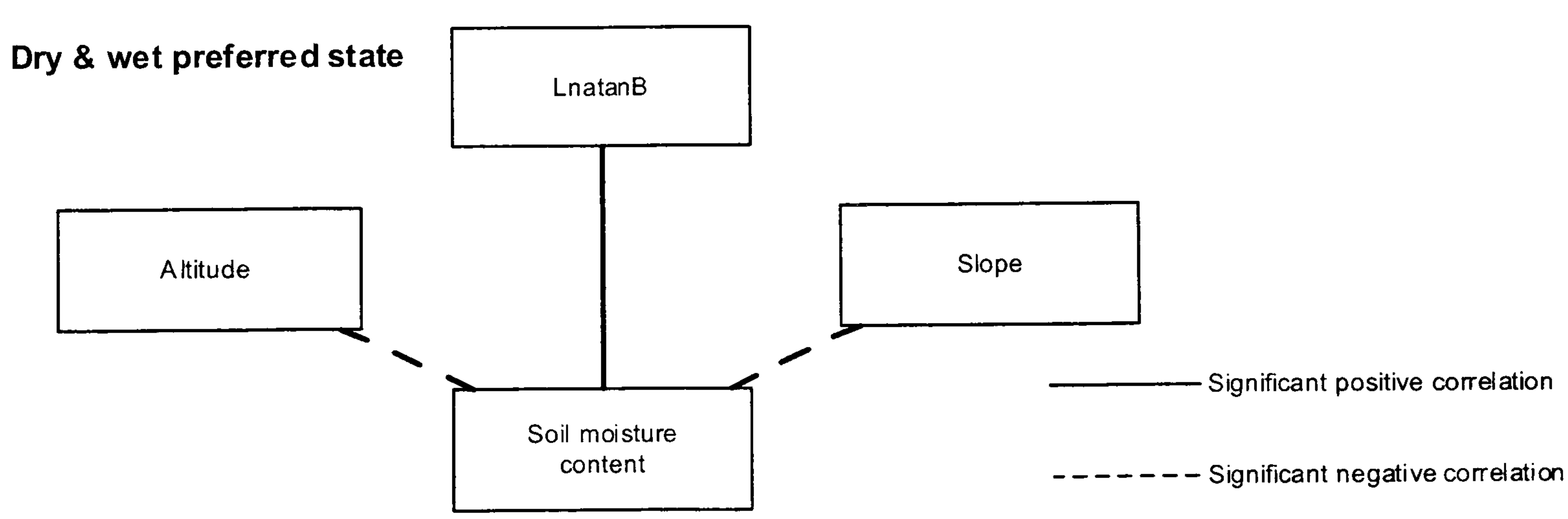


Figure 8.12: Causal-relationship diagram between topography and soil moisture.

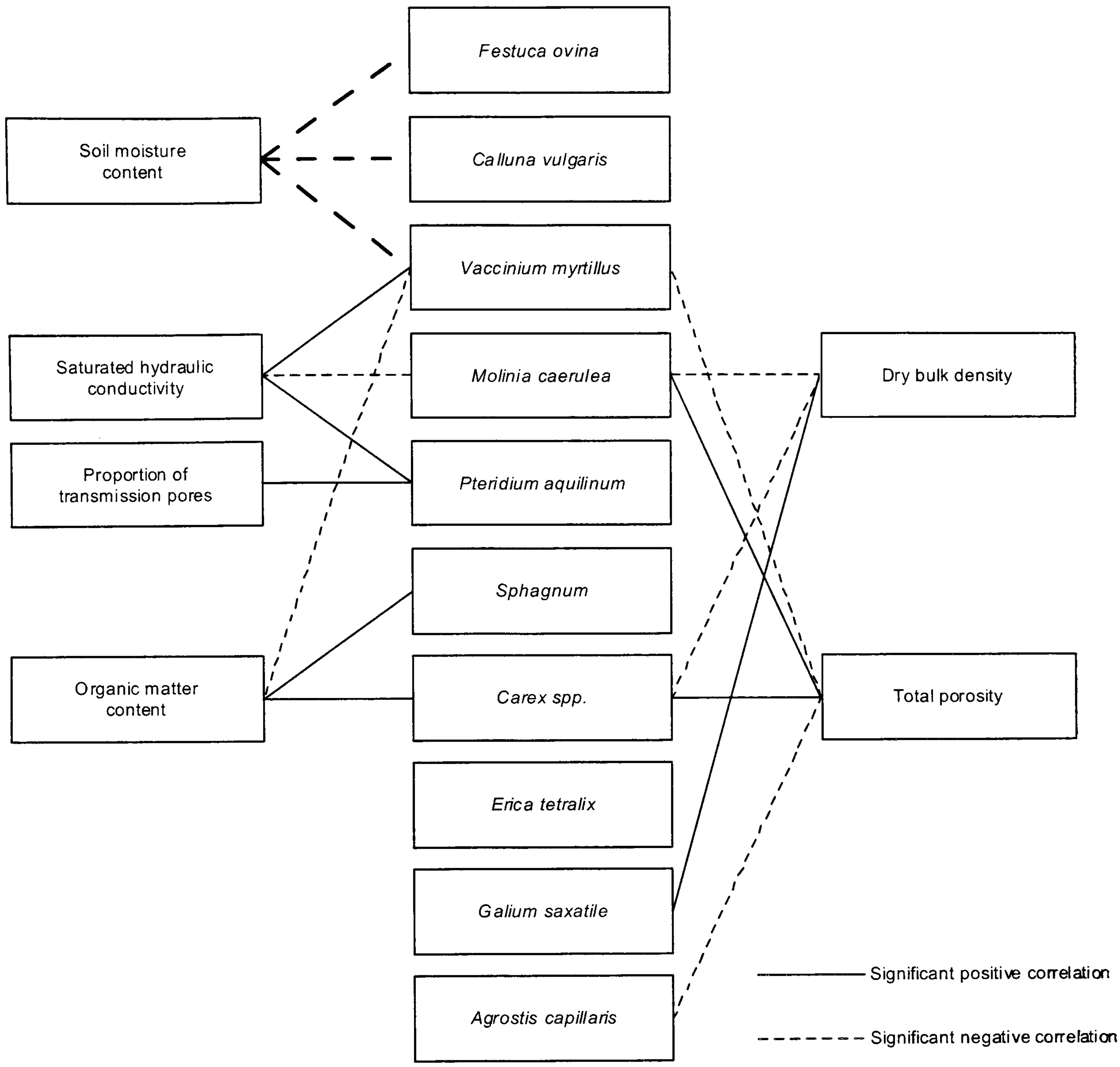


Figure 8.13: Causal-relationship diagram between soil properties and vegetation species.

8.5 Grazing effects on soil properties

8.5.1 Organic matter content and bulk density

In Section 7.3 results were presented on the difference in soil properties under different vegetation types and that the different vegetation types are associated with different grazing pressures. If it is assumed that this association is also valid within the TDR grid, these differences in soil properties may (partly) be attributed to stocking rates.

It was shown that organic matter contents under SG and BG were significantly lower in the upper soil horizons (0-3 and 4-7 cm) than under HG and GG (Section 7.3). No significant difference was found for the deeper soil layers. Especially SG, but also BG showed a relatively high stocking rate (Section 8.2.3). The explanation for this lower organic matter content under SG and BG could be lower inputs due to lower biomass and higher loss due to vegetation removal by grazing animals (Blackburn, 1984). However, this conclusion is based on the assumption that the vegetation reflects the grazing density throughout the catchment.

Other researchers also have found reduced organic matter contents with increased management pressures in otherwise similar soils (Pulleman *et al.*, 2000; Hao *et al.*, 2001). Droogers *et al.* (1997) and Pulleman *et al.* (2000) showed that the organic matter of the topsoil could be used as an indicator of past management in arable land and pasture conditions in the Netherlands. The fact that the difference is found only in the topsoil of the study area may be explained by the relatively recent change to a different vegetation type in comparison to the soil forming time scale.

Bulk density values at 0-3 cm soil depth were significantly higher in SG and BG than in HG and GG (Section 7.3). Below this depth, the difference becomes not significant. Two reasons for this increase in bulk density with depth could be given. Firstly, a lower organic matter content inherently causes an increase in bulk density, as the density of the organic fraction is much lower than that of the solid soil fraction (Rowell, 1994; White, 1997). Secondly, trampling and compacting even by a relatively small amount of livestock on peaty topsoils could cause a direct increase in bulk density, but only close to the soil surface (Evans, 1977; Evans, 1990).

8.5.2 Total porosity and the soil water release curve

The soil water characteristic curve affects the soil water movement through time (Chapter 6). Above a certain soil moisture threshold, the transmission pores in the soil fill up, with important consequences for soil water movement on the hillslope (Section 6.5). In order to study the effects of different grazing pressures on soil moisture dynamics, soil water release curves under different vegetation types need to be compared.

The 23 curves were split into the four different vegetation classes, as derived from the air photo classification and consequently averaged per class. So for each depth and vegetation class, a water release curve was established (Fig. 8.14).

Although the sample numbers were low (BG consisted of nine samples, SG of two, HG of seven and GG of five), a distinct difference could be found. The SG and BG classes show a significant lower total porosity at 0-3 and 4-7 cm depth ($p < 0.05$, Table 8.9). At 4-7 cm soil depth, these classes show a significantly lower porosity at all soil suction classes (0, 30, 50 and 100 cm). At greater depths, the difference in water release curves seems apparent, and a trend towards lower retention curves under the SG and BG classes occurs. This would suggest that if grazing levels are higher under SG and BG, a change in rooting system would cause the difference in water retention curves, as trampling only has an effect on the uppermost topsoil. Unfortunately, this trend is only statistically significant ($p < 0.10$) at a limited set of depths and soil suctions (Table 8.9), possibly due to an increase in standard deviation of porosity with depth. Possibly, the sample size was too small to filter out the subtle differences, and therefore a relatively low significance level was used.

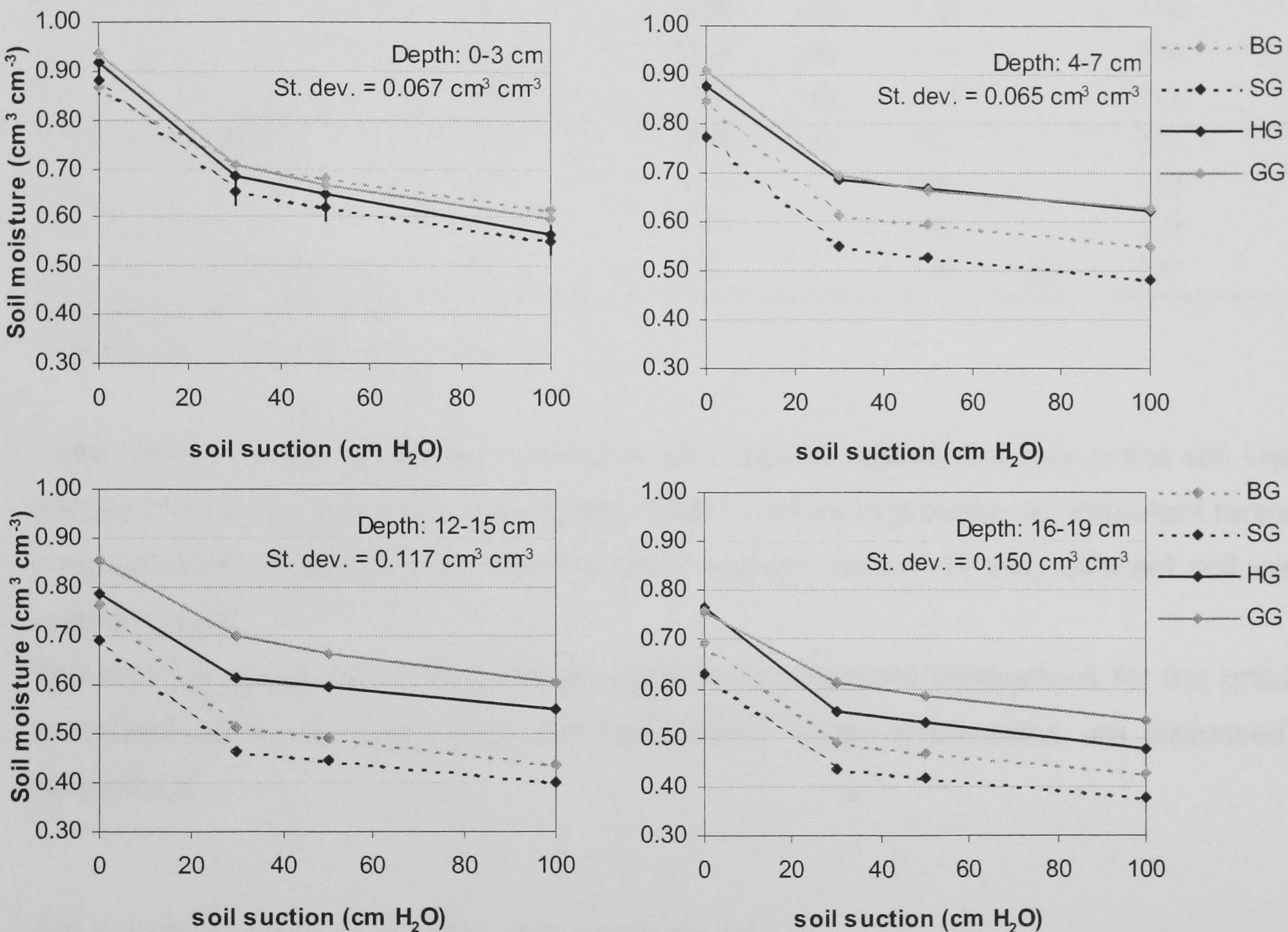


Figure 8.14: Water release curves per depth and vegetation type. Curves are medians.

Under direct increased grazing pressure, it could be expected that the largest (transmission) pores collapse at an earlier stage due to compaction (Ferrero, 1991; Profitt *et al.*, 1995). This implies that the relative proportion of the different pore size classes would be altered. The shape of the water release curve is a measure for the distribution of the different porosity classes. If it is assumed that the vegetation classes reflect the different grazing pressures within the TDR grid, it could be expected that a difference in the shape of the water release curve would be apparent close to the soil surface. However, the shape under different vegetation classes is not statistically different. This was tested by comparing the ratio between the slope of the curve between the 0-30 and

30-100 cm suction intervals. This result implies that, although the total porosity under different vegetation types is significantly different, the porosity distributions are similar.

Table 8.9: Results of the Kruskal-Wallis test on the difference between water release curves under different vegetation.

Porosity (Φ)*	pF	Kruskal Wallis test statistic (H_{KW})							
		0-3 cm	**Signif	4-7 cm	Signif	12-15 cm	Signif	16-19 cm	Signif
Φ_0 (Φ_{total})	0	7.59	yes	9.47	yes	2.05		1.36	
Φ_{30}	1.5	0.44		10.39	yes	4.45		1.06	
Φ_{50}	1.7	0.87		10.44	yes	5.16		1.06	
Φ_{100}	2	1.49		9.71	yes	4.45		1.03	
$\Phi_0 + \Phi_{30} + \Phi_{50} + \Phi h_{100}$		0.43		10.99	yes	3.67		1.19	
Φ_{trans}		3.25		4.79		4.32		0.83	
Φ_{trans} / $\Phi_{storage}$		0.25		1.44		2.09		0.32	
Percentage of transmission pores		2.94		5.56		7.39	yes	1.51	

* Φ_{30} = Porosity at h = 30 cm H_2O

***Significant (p < 0.10) if H_{KW} > 6.16 (df = 3)*

Total porosity is also positively correlated with organic matter, but only in the soil layers deeper than 3 cm. Therefore, the organic matter content is probably an important factor in determining the total porosity, and this could explain the significantly different soil water release curves.

The findings presented in this section could have important implications for the grazing pressures within the catchment, although subtle. These implications are discussed in Section 8.6.

8.5.3 Soil moisture variability in the grazing grid

A Kruskal-Wallis test (non-parametric data) was carried out to test the difference in soil moisture on different dates with different vegetation in the grazing grid. For the vegetation data, the classification from the air photo was used (Chapter 7). The results (Table 8.10) show a significant difference with 90% confidence in mean soil moisture contents between vegetation classes.

Although n is low in the case of SG (5), soil moisture contents within this vegetation class are significantly higher than soil moisture under other vegetation types. This effect is not only apparent in the top 20 cm (TDR), but also in the top 6 cm (thetaprobe). These analyses suggest a significant increase in soil moisture in areas with short grass, which coincide with heavy grazing. There was no indication of a difference in variance. Evans (1998) reported that the wetness of the soil increases below the rooting depth. As this rooting level is negatively related to grazing pressure, this could also have an effect on the soil horizons above. However, no soil moisture measurements below rooting depth have been carried out here.

Table 8.10: Results of the Kruskal-Wallis test between soil moisture content in different vegetation types within the grazing grid.

	n	θ_{TDR} 25-10-1999	θ_{TDR} 15-11-1999	$\theta_{thetaprobe}$ 15-11-1999	θ_{TDR} 26-11-1999	θ_{TDR} 02-12-1999	slope	lnatanb
Bracken & Grass	50	0.584	0.559	0.642	0.585	0.572	7.3	7.8
Short grass	5	0.624	0.612	0.667	0.638	0.623	7.9	7.6
Gorse / Grass	10	0.587	0.560	0.640	0.589	0.578	7.6	7.7
T_{KW}		5.11	8.09	6.87	7.16	8.84	0.05	0.64
p		0.078	0.018	0.032	0.028	0.012	0.978	0.725

n = 65, p < 0.10

Values indicated in grey are not significant

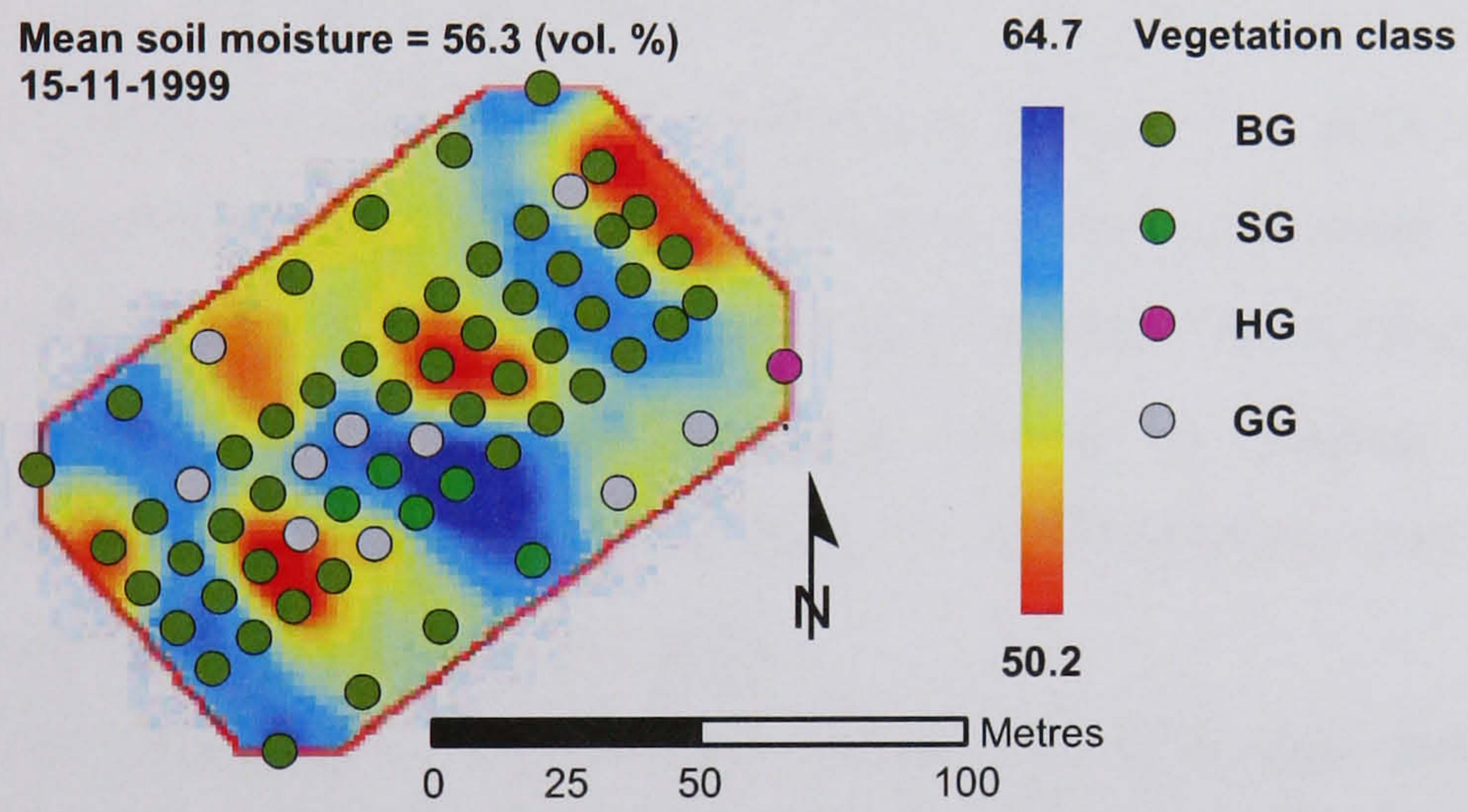


Figure 8.15: Kriged soil moisture plot of grazing grid and vegetation classes.

A geostatistical approach also showed the relation between vegetation and soil moisture content. Fig. 8.15 shows a kriged soil moisture plot (15th of November 1999) in which the vegetation classes were superimposed on each TDR location. Clearly, the SG area near the centre of the plot shows a relatively high soil moisture content. No significant differences between groups in topography (slope and topographic index) were identified as is shown from Table 8.9, so an effect of topography on soil moisture could be excluded. Therefore, within the grazing grid soil wetness appears to be higher in areas with increased grazing pressure under similar topographic conditions, albeit subtle.

8.5.4 The impact of grazing on soil moisture: discussion

Soil moisture contents vary widely with vegetation and grazing pressures, but also with slope and topographic index (Chapters 6 and 7). Between air photo vegetation classes, soil moisture values in the TDR grid were significantly lower under vegetation groups, which were typified by the highest observed grazing pressure (SG). The group with the second highest stocking density (BG) was characterised by significantly higher soil moisture values. However, the topography within the TDR-grid also showed a wide range of different conditions. The slope angle under the vegetation type with the highest grazing density (SG), was significantly higher (with about 6 to 7°) than all other groups. Gradient is negatively correlated with soil moisture content (Section 7.5). Slope angles in vegetation group BG were not significantly different from the remaining vegetation groups, HG and GG.

Soil moisture values measured over the entire hillslope (Section 6.4.4), show significantly higher soil moisture contents under both BG and SG, whereas the difference in slope angles was much lower (a difference of about 2°). Although this difference in slope angles between groups was still significant, this was mainly due to the large sample size. In practice the differences were much subtler, increasing the likelihood that soil moisture increases with vegetation groups related to grazing pressure. Increasing topographic index values showed an increase in soil moisture, and showed a similar effect between vegetation groups as gradient.

The combination of the results of the main TDR-grid, the hillslope soil moisture experiment and the grazing grid suggests that soil moisture levels could be higher in heavily grazed areas. This is only valid under similar topographic conditions, expressed as gradient and topographic index. However, when the topography is the same, higher soil moisture contents might not only be a direct consequence of grazing (*e.g.* trampling). Soil properties like organic matter content and bulk density also influence soil moisture (Chapter 6) and vegetation and vegetation change are controlling soil moisture as well. Although many factors therefore influence soil moisture, grazing certainly is one of these factors, albeit indirect and subtle.

8.6 Implications of land management

The purpose of this section is to compile all findings in relation to the effects of management on soil and hydrology. In Section 8.6.1, grazing management will be related to the hydrological behaviour of the catchment. In Section 8.6.2, the results of the burning experiments are summarised and the implications of fire on the hydrology at the catchment scale are discussed.

8.6.1 Grazing management

Radical changes in the properties of the topsoil (*e.g.* by trampling; Evans, 1997) or, on Dartmoor, the subtle change to a different vegetation composition could lead to different porosity distributions in the soil. Consequently, a shift in the wetness threshold value could alter the connecting and disconnecting behaviour of the soil and therefore the relative importance of the different water pathways of the soil (Grayson *et al.*, 1997).

In the main TDR-grid, the organic matter content and the total porosity are positively correlated with soil moisture, while the relationship between bulk density and soil moisture content (in the wet preferred state only) is negatively correlated (Fig. 8.11). Under increased grazing pressures organic matter content is significantly lower, and consequently, total porosity is also lower, in the top 7 cm. The bulk density is therefore lower under higher stocking densities, but this was only observed in the top 3 cm. Therefore, it could be expected, that soil moisture levels under higher grazing pressure had to be lower. This was indeed observed in the main TDR grid.

The key to the effect of grazing on the hillslope and catchment hydrology lies in the water release curve. It has been observed, that hillslope soil moisture threshold between the 'dry' and 'wet' preferred states coincides with the filling of the transmission pores, and this volume could be deducted from the water release curve. Under higher grazing pressures, the total porosity is significantly lower in the top 7 cm. Although not statistically significant, a trend appears in a downwards shift of the water release curve (Section 8.5.2). The lack of significance is probably due to the limited sample size, especially for the SG vegetation class.

Therefore, in heavily grazed conditions, the change from the heterogeneous locally controlled state could occur at an earlier stage than in areas of low grazing intensity, because the wetness threshold is reached earlier. Inevitably, water will be moving down the slope relatively quickly and the indirect effect of grazing will be an increase in river discharge. However, this impact is very subtle, especially when taking other factors into account that have their effect on soil moisture and soil moisture patterns. A study focussing more closely on the water retention characteristics of the topsoil is needed to fully explore the importance of this soil property.

On an annual time scale, during the winter this change in water release curve could mean that relatively more water is transmitted from more heavily stocked areas than under low grazing. Conversely, during the summer, the soil is storing less water, which will lead to lower stream discharge levels in drier periods. However, it has to be taken into account that the grazing levels as observed in the study area are representative for the summer period, and no data were available for winter.

Evans (1977; 1990) also showed this effect of increasing stream runoff with increasing sheep numbers, using long-term data of the North Derwent catchment in Yorkshire between 1944 and 1973. He showed that the stream runoff as proportion of the rainfall increased, and related this not only to sheep numbers, but also to the vegetation change related to this increase. Heather and *Vaccinium myrtillus* declined and an increase in the extent of grassland was observed (Evans, 1990). Sansom (1996) described similar effects in the Dales. Four major floods were reported over 13 years, combined with relatively low summer flows in the area. Although these researchers used a 'Black Box' approach, their conclusions support the results of grazing on catchment hydrology as presented here.

8.6.2 Conclusions and implications of burning at the catchment scale

Soil moisture contents in the upper 6 cm of the soil do not change significantly over the course of a burn. This was both found in the burning experiment, as well as soil moisture measurements carried out after a farmer's burn. This can partly be attributed to the depth, over which the soil moisture was measured, as this is a relatively thick layer. It was shown that temperature levels in the soil hardly increase at a depth greater than 1 cm. Other research is in line with these findings (*e.g.* Forgeard and Frenott, 1996). This shallow impact of the fire subsequently only reduced the soil water content in the uppermost layer. Over a depth of 6 cm, this slight decrease is averaged out. Also the time factor involved in the typical winter Dartmoor burn is of importance, as the fire moves relatively quickly and does not reach very high temperatures. This was measured within the burned plots, but also observed in burns carried out by farmers in the area, and was shown to be typical for Dartmoor.

On the longer term however, the burn affects soil moisture. In summer conditions, when the soil moisture status is low, the water content of the top 6 cm of burned soils is significantly higher than under unburned soil. Although the soil surface is probably drying out relatively quickly due to exposure to sunlight, deeper in the profile the water content is depleted quicker due to transpiration by vegetation. So in burned conditions, soil moisture levels are higher over the top 6 cm. If large areas would be burned at hillslope scale, this could mean that in dry conditions, burned areas could have a lower water holding buffer and reaches the threshold to the wet preferred state at an earlier stage, and therefore shed water earlier than unburned areas.

The rainfall simulation showed no difference in burned and unburned areas in terms of runoff, erosion and wetting up through time. Over the period of one hour of simulation, no overland flow was observed. However, although the rainfall amount was relatively large, this situation might not be representative for typical storm and conditions within the watershed. Rain events are often much longer, and in other locations in the catchment, bare soil has been observed producing a sediment output in (near) saturated conditions. Although soil moisture values were high during the experiment, the rainfall simulation was conducted after several weeks without rainfall and water added to the soil was possibly stored. Therefore, it can be concluded that in relatively dry conditions, overland flow will not cause problems within the area. Results cannot be extrapolated to wet conditions however and whether during these situations overland flow might occur remains to be seen. Moreover, these findings are valid for the short term directly after the burn only, and no data is available for the study area for the longer term.

8.7 Management, vegetation and soil properties: a conceptual model

After presenting and discussing the different influences of the moorland system within the catchment area, a model can be proposed with the aid of the diagrams introduced in Section 8.4. The most important relationships, based on significant differences between the various vegetation groups (this chapter) and the regression analysis between soil moisture and environmental variables (Chapter 7), are depicted in Figure 8.16. The relationships differ between the wet and dry preferred states and are discussed in the text. The relationships shown are mostly at the plot scale, but topographic components, operating at the hillslope scale, have been included to complete the diagram.

The above diagrams have been adapted to fit in the land management factors of grazing and burning, but also focus on soil moisture and porosity, as these soil characteristics have been shown to be crucial to the river discharge in the study area. Therefore, not all components as shown in Figure 8.11, 8.12 and 8.13 are shown here, as the emphasis is on the land management impact on the soils and hydrology. The figure should be as a tool to concentrate on the land management impact at the catchment scale. As previously, dotted lines reflect negative correlations, whereas solid lines denote a positive relationship ($p<0.10$). Also, the relationships are two-way in some cases, but only one-way in others. Correlations between certain depths also have been simplified, following the explanation of Section 8.5.

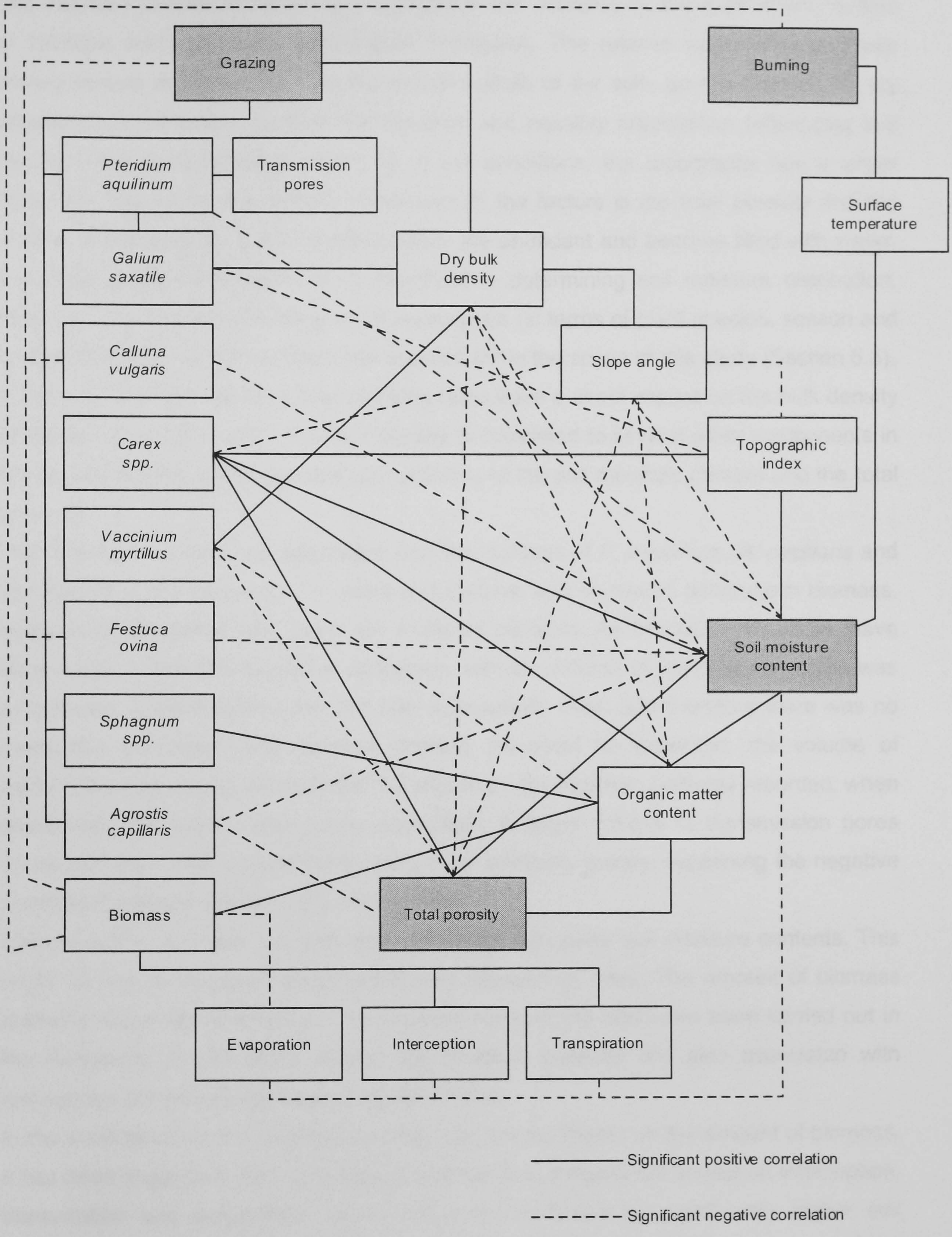


Figure 8.16: A conceptual model of the moorland management system and its effect on porosity and soil moisture content.

Soil moisture content and porosity are, together with topography, the main driving factors of hillslope and catchment hydrological processes. The relative importance of these driving factors depends highly on the wetness state of the soils on the hillslope. In dry conditions, local factors such as transpiration and possibly interception influencing soil moisture are more important, whereas in wet conditions, the topography has a larger influence. The key to the relative importance of the factors is the total porosity and the volume of transmission pores. If these pores are abundant and become filled with water, the slope angle will become more important in determining soil moisture distribution. However, the extent of the influence of interception (in terms of plant species, season and rainfall intensity) has not be taken into account within the scope of this study (Section 5.5).

It has been implied that increased stocking rates have a direct impact on the bulk density of the top 10 cm of the soil. The bulk density is correlated to several other components in the model, but the most important connection is to the soil moisture content and the total porosity.

High stocking densities are associated with the increase of *P. aquilinum*, *A. capillaris* and *Sphagnum*, and a decrease in *F. ovina* and *Calluna*, and an overall decrease in biomass. Bracken is associated with lower soil moisture contents. As bracken roots often leave large pores in the soil, a positive correlation with the volume of transmission pores was established. Transmission pores are only occasionally filled, and therefore there was no correlation with mean soil moisture content. As could be expected, the volume of transmission pores was correlated to the maximum soil moisture contents recorded, when presumably the transmission pores were filled. A larger volume of transmission pores could indicate a drier soil, as these pores drain relatively quickly, explaining the negative correlation between bracken and soil moisture.

Calluna and *A. capillaris* are both also associated with lower soil moisture contents. This might be due to increased transpiration and interception rates. The amount of biomass probably has a similar effect, but no measurements of this kind have been carried out in the framework of this study. Higher soil moisture contents are also associated with *Sphagnum*, but only via the organic matter content.

In the short term (up to 6 months), burning has a direct impact on the amount of biomass. It has been suggested, that a decreased biomass has a significant impact on interception, transpiration and evaporation, which has been confirmed by significantly higher soil moisture levels on burned plots under dry summer conditions. However, no detailed information has been obtained in the catchment area.

Burning hardly affects the soil moisture content over the course of a the burn in winter conditions, as no difference in moisture levels could be distinguished in the top 6 or the top 20 cm of the soil after a fire. As was shown in Section 8.3.2, only an increase in temperature was found in the uppermost topsoil, probably reducing soil moisture contents at this shallow level. The effect of summer burns on moisture levels has not been studied.

This conceptual model (Fig 8.16) shows the complexities of the relations between the different components of the moorland system. It can be concluded that land management has a subtle effect on the hydrology of the study area. The direct effect is limited to the uppermost topsoil only. Indirectly, the impact is complex and not always significant. However, the impact of land management is detectable and conclusions from this study should be considered for future management in the area. Therefore, due to the intensified land management, the moorland hydrological system is being forced to adapt. This continuous change has altered and probably is still in the process of altering the vegetation, soils and hydrology of the study catchment.

In this conceptual model, no time factor has been added. It must be clear that the components and processes within this system act on very different time scales. The removal or change of vegetation by any means can occur within a relatively short period, whereas soil forming factors based on the vegetation type need much more time to adjust. The timescale on which soil properties are being changed in the study area are unknown, as is the time period required to return to more natural conditions. This needs to be taken into consideration when decisions are being made on the management of the land.

Chapter 9: Synthesis and conclusions

9.1 Introduction

The purpose of this last chapter is to synthesise and summarise the findings and conclusions of the research. The structure of the chapter utilises the same framework as the thesis and focuses on the objectives stated in Chapter 1. These objectives fall into two categories: (i) hydrological processes and (ii) land management. Firstly, the hydrological behaviour of the hillslope and its influence on runoff generation in the catchment is addressed (Sections 9.2 to 9.4) and secondly the way in which land management can affect the hydrology is discussed (Section 9.5 to 9.9). The objectives are repeated below:

1. **Hydrological processes**

   1.1 To study the hydrological behaviour of a Dartmoor stream. The hydrological processes determining the rainfall-runoff response at the catchment scale will be investigated;

   1.2 To establish the relative importance of topography, soil physical characteristics and vegetation to soil moisture organisation at the plot and hillslope scale;

   1.3 To investigate the role of soil moisture patterns at the hillslope scale in runoff generation.

2. **Land management**

   2.1 To investigate the relationships between grazing densities and vegetation composition at the catchment scale;

   2.2 To assess the influences of different grazing pressures on soil properties at the hillslope scale;

   2.3 To examine the effects of heather burning on the soil and vegetation cover at the plot scale in order to estimate its influence on soil hydrology;

   2.4 To consider the implications of the research results for grazing and burning management of the Holne Moor catchment and to extend the findings to other areas of the Dartmoor Commons.

9.2 Hydrological processes at the catchment scale

9.2.1 Stream discharge and the rainfall-runoff relationships

The first objective was to investigate the hydrology of the Venford catchment. Discharge measurements were taken at two scales – the entire catchment (61 ha) and the headwater catchment (12.1 ha).

From storm event rainfall-runoff response curves, it was evident that the stream responded rapidly to rainfall. Times of concentration were relatively quick (around 90 mins) and average recession times were also short (8 hours). No significant difference in response times was observed between the upper and whole catchment. Stream discharge rose rapidly in response to rainfall. Flow duration curves showed that flood discharge levels were nearly an order of magnitude higher than average flows. Such a "flashy" behaviour is typical of headwater catchments with peat soils (Weyman, 1974; Dunne and Leopold, 1978; Burt *et al.*, 1990). This could indicate a catchment of limited storage capacity (Weyman, 1975), as rainfall is quickly converted into river discharge without first going into storage.

Rainfall-runoff ratios (Section 5.2.5) gave an indication of the proportion of rainfall that ultimately produced runoff (Chappell, 1990) within the two (sub) catchments on a multiple rain event scale. Values were close to 1.0 in the winter period, showing that (nearly) all rainfall is converted into river discharge. High antecedent wetness conditions, the lag between rainfall and runoff, groundwater discharge, low evapotranspiration rates and low interception values could yield high ratios, in which rainwater from a previous period could be discharged.

During the summer months, the soil water storage potential increased, due to higher evapotranspiration rates and less rainfall than during the winter period, resulting in lower antecedent moisture conditions. This storage potential combined with groundwater recharge resulted in a decrease of rainfall-runoff ratios to around 0.4, as rainwater was stored in the soil. During winter, rainfall-runoff ratios at the entire catchment scale were significantly higher than ratios within the upper catchment. Additionally, at event level, an analysis of the rainfall-runoff response showed that the volume of storm runoff per unit area was on average 1.11 times larger at the entire catchment scale than for the upper watershed over the recording period (Section 5.3). In summer, the difference was negligible. The essential difference between the long-term rainfall-runoff ratios and the short-term storm runoff was that baseflow was not incorporated in the latter.

It could therefore be concluded, that during the winter period, higher baseflow levels were generated per unit area from the entire catchment than from the upper watershed, whereas in the summer period this difference was negligible. Additionally, higher discharge levels per unit area were associated with storm events (*i.e.* stormflow) at the whole watershed scale than for the upper catchment. However, these vary through the season to a lesser extent than the baseflow levels. The difference of rainfall-runoff ratios and storm runoff volumes could be attributed to differences in topography, soils and vegetation in the two catchment areas.

9.2.2 Factors influencing the runoff per unit area

As areas with higher topographic index values are more hydrologically active (Knapp, 1978; Beven, 1999), lower topographic values in the upper catchment in comparison to the whole catchment could explain a generally lower discharge per unit area from the upper catchment, and therefore a lower rainfall-runoff ratio. In contrast, the larger proportion of steeper slope angles within the upper watershed suggests better drainage of this subcatchment. However, topography in combination with local soil properties provided a better explanation of the variation in discharge per unit area between catchments.

Soils in the upper catchment, especially on the higher parts, consisted of deep peats on gentle slopes. This combination resulted in areas with high water storage potential, suggesting a lower rainfall-runoff ratio. This storage potential could explain the difference in baseflow levels between catchments. During winter, the deep peats in the upper watershed retained and stored the water for longer, whereas in the lower regions of the catchment, the storage potential was more limited, and more water was discharged as baseflow.

Regular field visits showed that there was a constantly saturated area in the valley floor, defined as the variable source area, covering about 6.8% of the upper catchment and 8.6% of the whole watershed. The variable source area is defined as the area that is hydrologically dynamic, which transports incident rain water relatively quickly to the stream, either as subsurface or as saturation overland flow (Anderson and Burt, 1990). During and directly after rain events, saturation overland flow was widespread within this zone. The proportion of the catchment occupied by this variable source area was around 1.27 times larger in the whole catchment than in the upper watershed and could help explain the higher storm runoff from the entire watershed. This is especially the case in winter, when the variable source area is at its full potential and the difference in quickflow from both catchments will be largest.

It has been shown (Burt *et al.*, 1990), that interception by grass and heathy species is much smaller than by bracken (up to 49% of the rainfall; Williams *et al.*, 1987). During the summer months, when the bracken cover is at its maximum, the interception of this species will be largest. It has been observed that the percentage area of bracken in the upper catchment is lower than in the whole catchment, suggesting that, at the whole catchment scale, a lower proportion of rainfall reaches the soil surface in summer than in winter. In addition to the variable source area, this could also account for the summer – winter difference in storm runoff volumes between the two (sub) catchments. However, interception has not been measured within this study.

9.2.3 Minimum contributing areas and the variable source area

Minimum contributing areas, which are a measure of the proportional area of the catchment that is minimally necessary to contribute to the runoff response, were subdivided into two different conditions: low-volume rain events with a rainfall of less than 20 mm, and larger rain events with more than 20 mm. During low-volume rain events, minimum contributing areas were generally lower than 9% of the catchment area (7% in the upper catchment). This means, that during these low-volume storms, only 9% of the catchment (which in this case equals the variable source area) is needed to contribute to the flow in the stream, assuming that all rainfall is converted into storm runoff (Section 5.4.2). In larger events, minimum contributing areas of up to 65% were required, indicating that at least this percentage of the area generated stream runoff. During extreme conditions, the effective hillslope length contributing to the stream runoff could be more than 200 metres on average over the watershed, which extends far beyond the boundaries of the saturated area observed in the variable source area.

9.3 Soil moisture organisation at the plot and hillslope scale

Following Objective 1.2, factors determining soil moisture patterns are described in this section. Within the TDR-grid, soil moisture patterns showed two distinctively different states. These 'dry' and 'wet' states (Section 6.4) were defined by the hillslope average soil moisture content, antecedent precipitation and the active distance derived from geostatistical analysis. The concept of two preferred soil water states, introduced by Grayson *et al.* (1997) was used as a framework for the spatial organisation of soil wetness in this study. During the dry state, the soil moisture patterns were very heterogeneous and showed a short spatial correlation. Local (vertical) water movements like infiltration and evapotranspiration mainly controlled soil moisture. Local vegetation cover and soil properties were therefore more important than topographic factors. This relationship was confirmed with the regression between soil moisture contents and topography and vegetation (Section 7.5).

The two different wetness states were separated by a hillslope soil moisture average of around 0.60 $cm^3\ cm^{-3}$. At the point scale, water release curves showed that on average over the 23 measured locations within the TDR grid, the transmission pores started to fill up near a hillslope average soil moisture content of around 0.59 $cm^3\ cm^{-3}$, which corresponded well with the wetness threshold.

In the wet state, soil moisture patterns showed a much longer geostatistical spatial correlation, combined with higher soil moisture contents above the wetness threshold. This was still below saturation: soils in the grid showed a total porosity of 0.80 $cm^3\ cm^{-3}$ on average on the hillslope over the top 20 cm. During these wet conditions, the organisation was much more controlled by topography than in the dry state. Therefore, the soil water could be redistributed laterally, showing a more homogeneous wetness pattern.

Tensiometer analyses (Section 6.6) demonstrated that most of the water did not infiltrate into the subsoil, forcing infiltrating water to be transported mainly laterally. Tensiometer data have demonstrated that soil suction in the topsoil was often in the range of 50 cm H_2O to saturation, showing that at least part of the transmission pores were filled. Lower in the profile, suctions were higher and, if it is assumed that water release characteristics were similar deeper within the soil, transmission pores were filled less frequently. When these pores are filled with air, they act as a barrier rather than a water conductor (Koorevaar *et al.*, 1983). Soil profile descriptions at the 23 locations within the TDR grid showed that, in most cases, an ironpan or a texture difference between top and subsoil could explain the difference in soil moisture behaviour.

9.4 The influence of soil moisture organisation on runoff generation

9.4.1 Soil moisture variability and runoff generation

The two different wetness states were reflected in the stream discharge behaviour (Objective 1.3; Section 6.5). During dry conditions, stream discharge only increased slightly with increasing soil wetness. The soil moisture patterns were heterogeneous and relatively drier areas on the hillslope acted as local sinks for water moving laterally from wetter areas. Soil water transport is mainly local due to infiltration and evapotranspiration. Even larger storms generate relatively small runoff volumes, as the response is derived from a relatively small saturated area near the stream. Such a small response could be explained by the variable source area mechanism proposed by Hewlett and Hibbert (1967). Minimum contributing areas calculations reaching values of up to 10% of the catchment areas corresponded well with the extent of variable source area (around 9%) observed in the field (Section 9.2) during these conditions. So, rainfall on the saturated areas adjacent to the stream was quickly converted into runoff, either as saturated overland flow or subsurface flow (Anderson and Burt, 1990). However, this concept of a runoff generating mechanism might be oversimplified, as there may also be a subsurface flow component draining from higher parts of the hillslope, especially during larger storms (Meyles *et al.*, 2002)

During wet conditions, at a soil moisture status exceeding the 0.60 $cm^3\ cm^{-3}$ wetness threshold, stream discharge increased exponentially with increasing average hillslope soil moisture content. This behaviour could be explained as a combination of the soil hydrology at the plot scale and spatial wetness organisation at the hillslope level.

At the plot level, the water release curves showed a break in slope between the higher and lower suctions on all measured water retention curves, at around 0.59 $cm^3\ cm^{-3}$ on average. At this suction, transmission pores are filling up (Rowell, 1994) and, as the soil moisture content rises above field capacity, the hydraulic conductivity increases significantly (Van Genuchten, 1980), enabling lateral subsurface flow.

At the hillslope scale, when lateral subsurface flow increased, soil moisture patterns became more homogeneously organised (Western *et al.*, 1999). Geostatistical correlation lengths increased rapidly. In these conditions, wet areas became more connected hydrologically and significant areas of the hillslope were therefore able to contribute to stream runoff. Consequently, discharge levels rose more quickly with further rainfall.

9.4.2 A possible water redistribution mechanism

In the wet state, the effective hillslope length becomes extended onto the higher, steeper parts of the hillslopes. This length combined with times of concentration during these conditions suggested that a water transport velocity of 9 to 90 $m\ hr^{-1}$ (much higher than the observed hydraulic conductivities) is needed to account for the peak in the stream. Overland flow is largely limited to the variable source area, suggesting that most of the water response is located in the (top) soil. Tensiometer data (Section 6.6) confirmed this. Velocities, similar to the ones presented here, found by other researchers (*e.g.* Gilman and Newson, 1980; McCaig, 1984), suggested that water could be moving down the slope by macropore or pipeflow. Indications of pipe springs were only locally observed however (Section 6.7). Several authors (*e.g.* Beven, 1981; Beldring *et al.*, 2000) have used a kinematic wave approach to explain the high velocities and the relationship between subsurface flow and river runoff, suggesting that the energy of the rainfall could be translocated through the soil. During wet conditions in the study area, kinematic energy waves are likely to be propagated downslope over large effective hillslope lengths and caused flow into the saturated areas, as the wet areas on the hillslope were well connected (Williams *et al.*, 2002)

9.5 Vegetation composition and grazing pressures

9.5.1 Vegetation classification within the study area

The current vegetation cover was related to recent grazing pressures, as long-term grazing data were unavailable for the study area. In the main TDR-grid, single plant species coverage was determined on all 151 grid nodes. Due to the complex relationship between single plant species and their environment (Rodwell, 1996), the vegetation was classified into groups or communities. With the use of a two-way indicator species analysis (TWINSPAN), four vegetation groups were established (Section 7.2.2). These communities were related to soil wetness and grazing pressure. Additionally, with the aid of a supervised air photo classification and field verification, four vegetation communities could be derived at the catchment scale. These were reasonably comparable with the TWINSPAN groups (Section 7.2.3) and therefore the air photo classes were a good reflection of vegetation groups within the whole study area. In order to facilitate the comparison of vegetation communities between different scales and to enable application in other areas on Dartmoor in future research, only the air photo classification was used to analyse the distribution of vegetation groups.

9.5.2 Grazing densities and spatial distribution of livestock

To obtain a distribution of livestock, the positions of sheep, cattle and ponies were recorded on maps on 15 separate occasions representative only for the summer period. The results obtained were combined with the air photo vegetation classification in a GIS to obtain a relationship between grazing densities and vegetation distribution (Objective 2.1). Cattle and ponies did not show a significant difference between vegetation groups. However, sheep grazing behaviour was more heterogeneous. In the short grass (SG) area, the sheep numbers observed exceeded the livestock units (LU) limits per hectare suggested by MAFF (1998) in the Dartmoor ESA scheme for Tier 1E. Sheep grazing in areas with bracken with undergrowth of short grass (BG) was also significantly higher than in the remaining two vegetation groups, but densities were just below the Dartmoor ESA guidelines. Sheep also tended to graze in the vicinity of the short grass area (Section 8.2.4), which was mainly in bracken. Therefore, the vegetation classes represented a range of different sheep grazing pressures in the area.

Over the whole catchment, however, sheep and cattle numbers were below the Tier 1E grazing limits on average, suggesting that the Dartmoor ESA guidelines (currently used by DEFRA) are a limited tool for controlling grazing, as it does not take spatial grazing variability into account. Hence, these guidelines should be adapted to a more area-specific basis and controls on sheep movements and monitoring should be introduced.

9.6 The influence of grazing management on the soil

9.6.1 Soil physical properties

When using the air photo vegetation classes for the sample points within the TDR-grid, several differences in the physical characteristics of the topsoil were found (Objective 2.2). Organic matter contents were significantly lower in the top 7 cm under bracken and short grass vegetation types. This implies that, with increased grazing pressures, organic matter decreased. This could be caused by a decrease in litter input due to either less biomass cover (heather species *vs.* grasses), but also because of biomass output by grazing livestock (Blackburn, 1984). Bulk density values were higher near the soil surface (top 3 cm) under vegetation types associated with higher grazing pressures. This could partly be due to trampling, which tends to affect only the very upper horizons of the soil (*e.g.* Evans, 1977; Ferrero, 1991). However, it was more likely caused by a reduction of organic material, which has a naturally lower bulk density than the mineral fraction of the soil. The total porosity was lower in the top 7 cm of the soil, as a consequence of both the increased bulk density of the top 3 cm and the decreased organic matter content of the top 7 cm. The origin of difference in organic material reduction might be attributed to a change in vegetation composition.

These results also have implications for water release curves. With increasing grazing pressure, the entire soil water release curve was shifted downwards (Section 8.5.2). At a depth between 4 and 7 cm, this was statistically significant in all wetness conditions. At 0-3 cm this was also significant near saturation. Although this effect was not significant deeper in the profile due to large standard deviations, the different water release curves below 10 cm depth suggested otherwise. It was therefore assumed that there was a trend towards lower retention curves with increasing grazing pressure, but more samples would be required to establish this more definitely. The similar shape of the water release curves indicated that there was no difference in pore size distributions between different vegetation groups.

9.6.2 Soil moisture characteristics

Analysis of the relationships between the mean soil moisture values from the three different soil moisture grids and vegetation groups indicated a trend of higher soil moisture contents with increasing grazing pressure. Mean soil moisture values within the main TDR grid revealed that the vegetation group with the highest grazing pressure showed significantly lower soil moisture values. However, soil moisture on the hillslope was not only determined by vegetation, but also by topography (Section 6.5.3). An analysis of the topography within the different grids revealed that soil moisture was negatively correlated with slope angle both in dry and wet conditions. A comparison of the different slope angles between the vegetation groups showed that the group associated with the highest grazing pressures also showed a significantly higher gradient (of 6 to 7°) than the other groups. However, within the grazing grid and the entire hillslope grid, soil moisture was significantly higher under increased livestock densities. This indicates that the slope effect on soil moisture content in this case is more important than the effect of grazing pressure. Within the latter grids, gradient differences between groups were much smaller (about 0.5 to 2°). It was therefore suggested that soil moisture levels increase with stocking density under similar topographic conditions. Yet, due to the complex relationship between the different factors determining soil moisture and the limited samples in the vegetation group with highest grazing pressures, the data could not be fully explored.

9.7 The influence of burning management

9.7.1 Burning characteristics

To address Objective 2.3, two burning experiments were carried out at the plot scale in the study area. Soil moisture characteristics were compared to two adjacent control plots, and all plots were on a soil of the Hexworthy series with an ironpan at around 50 cm depth. Fuel loads were estimated to be around 9000 kg ha^{-1}, which is typical for heather in the building phase (Kayll, 1966; Gimingham, 1975). Temperatures just below the canopy at ground level reached maximum values of between 80 and 410°. At 3 cm soil depth, the increase in temperature was negligible. The burn was comparable to a farmer's controlled burn, in terms of intensity and speed. It was concluded that, in line with the findings of other researchers (*e.g.* Gimingham, 1975; Forgeard and Frenot, 1996), prescribed winter burning only removes the woody biomass and only has a limited effect on the topsoil.

9.7.2 Heather burning and soil moisture characteristics

Rainfall simulation experiments on the burned and control plots generated no overland flow. Rainfall intensities were relatively high, and continued for 60 minutes. Typical Dartmoor rainstorms often show a lower intensity, but last much longer (Meteorological Office, 1983). For the measured conditions, it was concluded that overland flow was probably not an issue at the plot scale within the catchment.

Soil moisture values did not decrease significantly during the burn. Furthermore, readings taken in plots burned by farmers in adjacent catchments did not show a different wetness between burned and unburned conditions on the short time scale. However, Ternan and Neller (1999) argued that at least some rainfall was needed between the burn and a second measurement to find an effect on soil porosity, as ash left by the burn may wash into the soil.

Within the plot experiment, however, no significant difference in wetness under burned and unburned conditions was observed up to two months after the burn, under wet conditions. In contrast, during dry summer conditions, soil moisture contents were higher under burned conditions in comparison to the control plots. Reduced transpiration rates due to burned vegetation could account for this. As a consequence, the topsoil had a lower water holding capacity. On burned plots therefore, soil moisture threshold values are reached at an earlier stage during rainfall, causing accelerated downslope movement of water. As the experiment was only conducted at plot scale however, this could not be verified at the hillslope level.

9.8 The likely impact of land management on runoff generation

Following Objective 2.4, the study results will be applied to the catchment and the Dartmoor Commons level in this and the next section.

The findings presented in this thesis suggest that land management within the study area could have an influence on the hydrology of the catchment, resulting in increased winter storm flows and decreased summer discharge. It should be stressed, however, that this influence is indirect and subtle. Stocking densities in the area were shown to be heterogeneous, caused in part by the heterogeneity of the vegetation distribution. The exact interactions could not be studied, because of the complexity of this relationship and the unavailability of long-term livestock density and vegetation data.

However, from the analysis it is clear that land management is indirectly influencing catchment hydrology: The interactions between land management and vegetation eventually change the physical soil properties, which in turn affect the hydrology of the hillslopes.

Higher soil water contents, reduced soil water storage space and a 'downward shift' of the water release curve may occur under vegetation types associated with higher grazing pressures and could cause a decrease in the threshold value between dry and wet states. As a consequence, less rainfall will be required to reach the threshold value. As the topsoil reaches the homogeneous wetness state, it will facilitate more rapid water movement down the slope than under less grazed conditions. This means that if larger areas are more heavily grazed, water will be 'translated' more quickly to the river, causing higher peak discharges. The reduced soil water storage space under more heavily grazed area also suggests that more water is being lost from the catchment in wet conditions. In drier periods, particularly in summer, this could result into lower soil moisture values and reduced baseflow levels, confirming the suggestions by Evans (1997) and Sansom (1999).

Although the study on the impact of burning on the soil has been restricted to the plot scale, a similar effect could be expected at a wider scale. Burned plots show higher soil moisture values under dry conditions, indicating that the threshold value from the dry to the wet state will be reached with a smaller input of rainwater than under unburned conditions. Where extensive areas are burned, these areas may become hydrologically active at an earlier stage, as also occurs in the more heavily grazed areas.

However, the position, distribution and fragmentation of the different vegetation groups, burned areas and grazing pressures are key issues. For example, if heavily grazed or burned areas are more fragmented and spatially heterogeneous, less grazed or unburned areas may be able to buffer the adverse effects, depending on local topography and the distance to the stream. Additionally, when heavily grazed or burned areas directly border the water courses or variable source areas, as is the case in parts of the study area, increased storm flow is more likely than if areas are separated by semi-natural vegetation zones under light grazing pressure. This buffer zone will take up excess water from higher up the slope and store it temporarily before it is discharged into the stream.

9.9 Recommendations

Future research following on from this thesis can be divided into two different, but not mutually exclusive, approaches. The first approach is to extend the investigation within the study catchment to increase knowledge on the processes influencing water routing (Section 9.9.1). The second approach is to extrapolate results from within the watershed to the whole of the National Park (Section 9.9.2). This approach is considered particularly important by conservation agencies and the National Park Authority.

9.9.1 Applications of the research results to the study area

Within the watershed, there are still several issues that need to be resolved. In terms of hydrology, further insights are needed into the (spatial) variability of soil and hillslope water pathways and the different mechanisms involved in water routing. These will help in assessing possible land management impacts during different conditions and within different areas within the catchment. The model proposed in this thesis, which focuses on the fast pathways, needs to be explored further. Tracer experiments, both at plot and at catchment scale could be useful in determining the origin of flood water i.e. distinguishing between 'old' water from the hillslope from macropore and/or pipeflow (mainly 'new' water).

At the plot scale, a similar exercise to that conducted by Rasmussen *et al.* (2000) could be used to separate out pressure waves and actual water movement. In this study, a soil core was taken and a tracer added at regular intervals (Section 6.7). This would enable pressure wave velocities for the catchment to be estimated more precisely. The dependence of pressure waves on soil moisture content should also be investigated at this scale, as this appears to be an important factor for water reallocation within the catchment. Additionally, experiments could be carried out using soil cores from sites under different grazing pressures to further examine the effects of land management on the soil water transport processes at the plot scale.

At the catchment scale, natural tracers (such as ^{18}O) are preferred in order to assess the relative importance of 'old' and 'new' water, as the application of an artificial tracer across the watershed (61 ha) would prove impractical. If carried out in both wet and dry conditions, this kind of experiment could provide insights into the different processes involved in water routing. The relative importance of the different pathways and mechanisms in different conditions could then be estimated with greater precision.

Another issue for further investigation are the actual processes behind different soil moisture levels under different vegetation types. This process is dependent on factors such as transpiration, evaporation, interception and rooting characteristics. The relative importance of each of these factors to soil water levels under different vegetation covers should be investigated. Results can then be related to season, antecedent wetness conditions, the different wetness states and soil physical characteristics.

The aim of this study was mainly focused on the topsoil. Further insight into soil water pathways in the subsoil is needed in order to quantify the proportion of water used for storage and as groundwater input, during wet and dry conditions, and in different seasons.

As no data were available on the grazing densities within the catchment, long term exclusion plots which prevent grazing could be used to study the effects of grazing on vegetation composition in combination with its effects on soil physical properties.

Although burning has been investigated within this study, the results are not comprehensive enough to extrapolate impacts at the watershed scale. A more detailed study needs to be carried out into the shallow effects of fire on soil and hydrology, including the effects of ash (re) deposition. One option is to carry out a burning experiment at another catchment, preferably to the more eastern moors, where *Calluna* stands are generally in a more healthy state. Long-term monitoring could be carried out to assess the impact of heather burning on the soil over the long term. A monitoring scheme of five to ten years would allow time for the heather to recover and the changing effects on soil characteristics to be identified.

Additionally, a fire experiment could be carried out in conjunction with farmers to ensure the burn is representative. This would mean burning on the hillslope scale and on a vegetation type, which is more typical of that being used for burning (*Molinia* and *Ulex spp.*). As some parts of the moors are currently being burned at regular short term intervals (two – three years), monitoring could also focus on such an area as well. It is of major importance however, that the impact of typical spring burns is separated from accidental summer burns. The swaling carried out by farmers is likely to be less damaging to soils and hydrology than accidental summer fires. Conditions are much wetter, it is controlled and maintained, and therefore the impact is much shallower. Summer burns, which were not part of the focus of this study, are uncontrolled and occur in drier conditions, and are therefore more likely to have a devastating local effect on wildlife, soil and hydrology (Goodfellow, 1999, pers. comm.)

9.9.2 Application of the results to the National Park

The study area is a typical East Dartmoor watershed. In order to estimate the impact of land management on the scale at which policy decisions are taken, a more regional scale needs to be adopted. Extending the research to other areas of Dartmoor, such as the Commons or the ESA scheme level, is therefore an important issue. Failure to scale up such studies diminishes their value into terms of informing policy and land management decisions. Extending the results in this thesis is therefore important in managing landscapes at a regional scale.

It has been argued that the spatial variability of the topsoil in the catchment area is of main importance to the hillslope and catchment hydrology. To apply the results to other areas on Dartmoor, similar analyses of vegetation and soil moisture patterns should be conducted in areas where soil and vegetation types differ from those in the study catchment to complete the picture. The blanket bog of the high plateaux of the moors should be taken into account for instance, as should the vegetation gradient from east to west across Dartmoor. Additionally, more detailed livestock density data should also be acquired for these regions. Neither has knowledge been acquired for the farming areas at the fringe of the moors, but they undoubtedly have their role on the regional hydrology. At this scale, the spatial variability of rainfall and the climate in general become more important issues.

For the Dartmoor area, a methodology is required to acquire landscape-scale variables from easily obtainable or readily available data. Research in North Devon using such data has yielded promising results (Van Soest, 2002). In this thesis changes in vegetation cover and patterns due to grazing pressures have reliably been estimated using aerial photography at the catchment scale. The Dartmoor National Park Authority has access to different sets of aerial photos, covering most of the moors between 1947 and 1992. The use of Remote Sensing techniques might be extended by using satellite imagery on the National Park scale in combination with field studies to establish the relationship between grazing pressure and vegetation types on a regional scale. English Nature is currently planning to acquire satellite imagery (Bates, 2001, pers. comm.) and the Dartmoor National Park Authority is planning to create a new set of air photos for Dartmoor (Goodfellow, 2000, pers. comm.).

If available, long-term rainfall-runoff data of the Dart and other rivers running off the moors could also be used to estimate changes in behaviour, similar to studies carried out by Evans (1996) and Sansom (1999). On Dartmoor, rainfall-runoff data could be used in combination of vegetation and livestock density increases over the last decades. However, this is only possible if farmers are willing to co-operate and make available records on livestock densities.

Using the knowledge based upon the results from topsoils within the study area, available soil maps could be used and extended to estimate the impact of land management on individual soil series. Further analysis of altitude, slope angle, aspect and topographic indices on regional scale is also important, and readily obtainable from digital topographic data.

In addition to the above recommendations, temporal factors also need to be addressed. On several occasions during this study, data covering a longer period would have given better insight into the effects of slowly intensifying moorland management. Over the last decades, several studies (*e.g.* Weaver *et al.*, 1998) or monitoring programmes (Goodfellow, 1999, pers. comm.) have been set up but unfortunately, were discontinued. Long term studies, such as on grazing exclusion plots, and long term data, for river discharge and stocking levels, could provide a solid base for a such a study. It would also provide material for comparison with studies carried out elsewhere (*e.g.* Evans, 1996). One major temporal issue is the response time of the soil after a change in vegetation.

Very little data is available on the amount of time required for soils on Dartmoor to adapt to alterations in vegetation cover. Organisations such as the Dartmoor National Park Authority, English Nature and the Environment Agency in co-operation with hill farmers and DEFRA should therefore consider setting up long-term soil and vegetation monitoring sites to examine the effects of land management in the moorland environment.

The longer-term issue of global warming is a crucial factor that has also received a lot of recent interest. Future change in climate will certainly impact on the results presented in this thesis, at catchment and National Park level, and will affect other moorlands. A recent study (UKCIP, 1998) on climate change has shown that summer rainfall in England and Wales has fallen, and winter rainfall has increased in Scotland over the last century. It also showed that the average annual temperature across England has risen by 0.5 °C during the 20th century. The different scenarios produced by the UKCIP programme suggest that winters will become wetter, the number of hot days per year will increase, and there will be a decline in number of cold days. These results and prognoses could mean a further increase in winter discharge levels and decrease in summer flows. Moreover, as heather on Dartmoor is growing at its wetness limit (Gimingham, 1975), this could mean a further decline of the extent of heather on Dartmoor. These studies should also be taken into account when assessing the influence of land management in the Dartmoor area in long-term studies.

9.9.3 Recommendations for future moorland management

The results presented in this thesis suggest that land management has an indirect effect on soil properties and hydrological response at catchment scale. This could have important implications for future grazing management in the area, especially if the results are replicated in other areas of the Dartmoor National Park (Section 9.9.2).

It has been shown that grazing is not distributed homogeneously in the study catchment. Some areas suffer from overgrazing, whereas other areas are well below the maximum stocking levels for ESAs suggested by MAFF (1998). From the soil moisture – stream discharge analyses it was evident that heavily grazed areas induce transport of water to the stream at an earlier stage than less grazed areas under similar topographic conditions. If heavily grazed areas are close to the stream therefore, this will have a direct effect on the rainfall-runoff characteristics of the stream. As areas with little or no grazing have a higher threshold to non-local soil water conditions, they will provide a buffer, (partially) storing water from areas with higher stocking densities upslope. If heavy grazing can be kept away from the stream or variable source area, the effects will be less, and buffering or zonation of grazing could mitigate the problem. This could only be achieved by fencing off particular areas, which is not possible on the Dartmoor Commons. Therefore either a change in seasonality of grazing similar to that already applied on the Commons, or a reduction in permissible stock units could be a solution from a hydrological point of view.

The results also highlighted the crucial hydrological role of vegetation types and their distribution. If hillslopes are homogeneously overgrazed, no buffer zones exist. Water can be shed over larger distances, directly into the variable source areas or streams, at a lower wetness level, increasing winter peak discharges and reducing low summer flows. If large areas of heather are present, more water can be stored in the soil and extreme water flow conditions can be avoided. Such areas of heather have to be sufficiently large to withstand grazing pressures from the boundaries of other, more palatable plant communities. Although heterogeneous vegetation communities have to be encouraged, they should not be allowed to become excessively fragmented. In summary, there is a close relationship between land management, soil properties and catchment hydrology in this headwater area. The implementation of the current ESA scheme on Holne Moor might therefore be a good start in avoiding further fragmentation of the vegetation mosaic. Such a strategy would also increase biodiversity, regulate water movement to the stream and enhance the quality of the upland environment.

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